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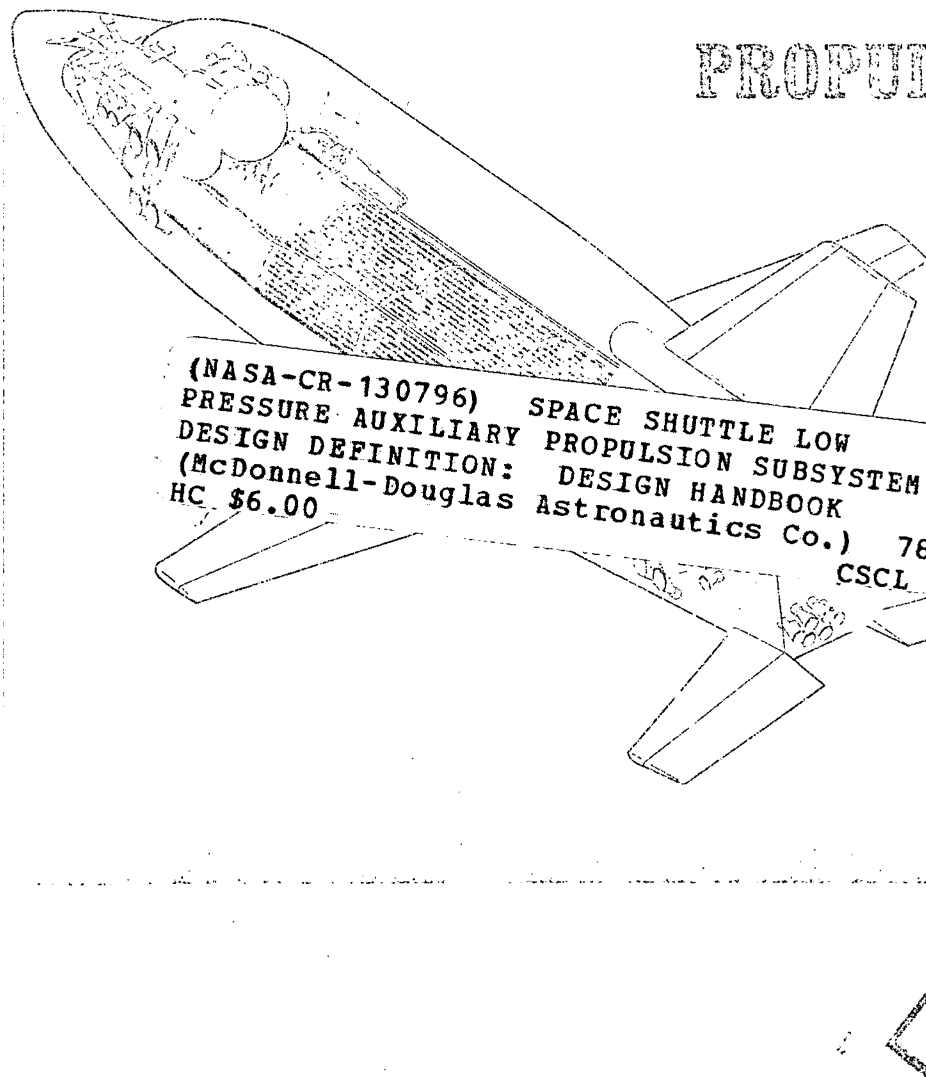
SPACE SHUTTLE LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM DEFINITION



DESIGN HANDBOOK

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

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SPACE SHUTTLE LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM DESIGN DEFINITION

CONTRACT NO. NAS 9-11012

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REPORT MDC E0301

DESIGN HANDBOOK

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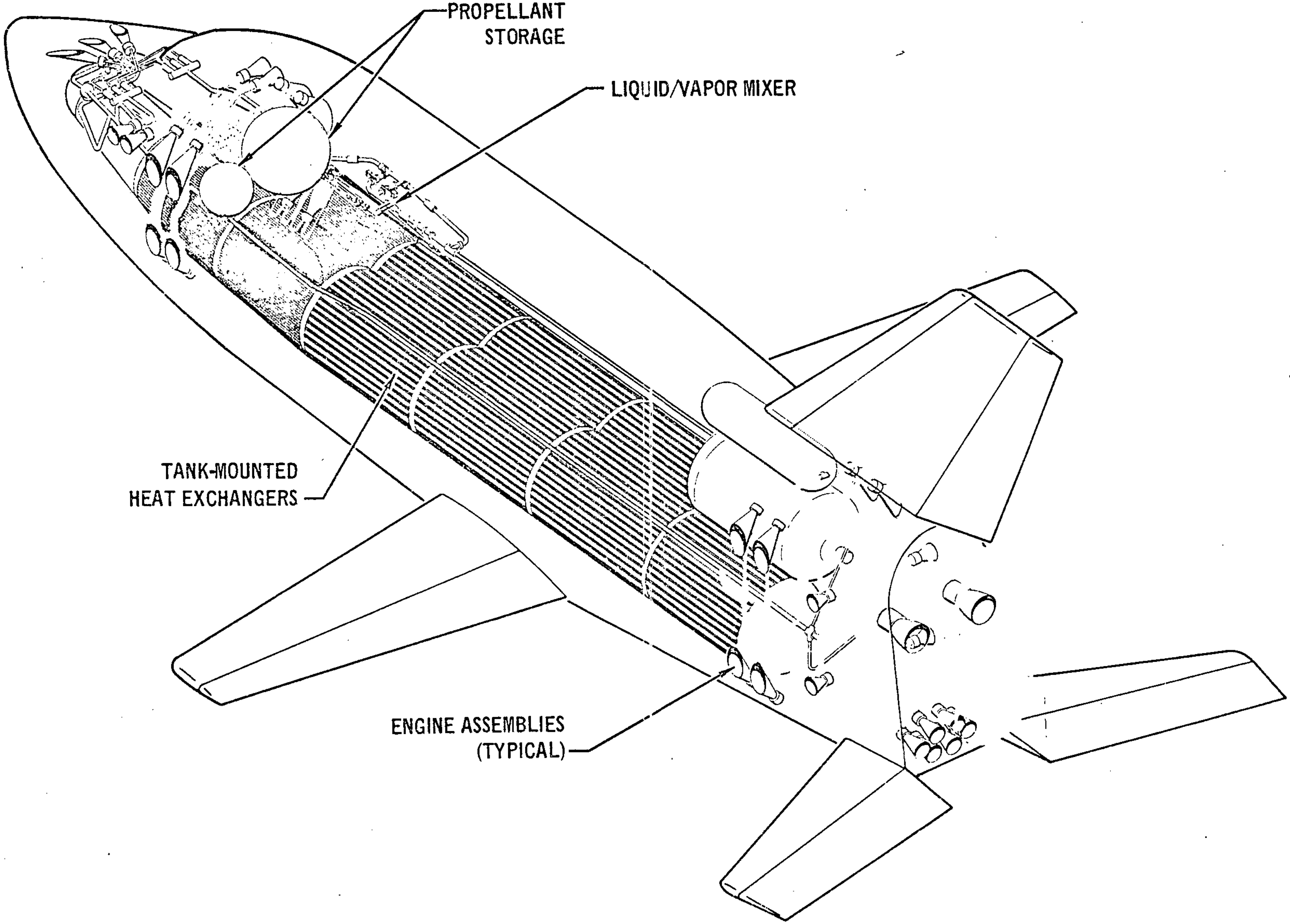
ABSTRACT

This handbook contains a detailed description of recommended low pressure auxiliary propulsion subsystems (APS) for a space shuttle orbiter and booster. The APS designs presented herein are the product of a seven month study to identify and evaluate APS concepts, and to perform in-depth design and performance analyses for the most attractive of these. The study was performed for the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas, under Contract No. NAS 9-11012.

Selected APS baselines use the main engine propellant tanks as low pressure gas accumulators. For the orbiter, propellants from separate liquid tanks are used for main engine tank resupply. Resupply propellants are first circulated through tubular, passive heat exchangers, where they are vaporized and superheated prior to injection into the main engine tanks. Warm propellant vapors from the main engine tanks are mixed with additional liquid propellants in a downstream liquid/vapor mixer and supplied to the engines at constant temperature and pressure (constant density). The booster APS requires no separate propellant storage, since propellant residuals, trapped in the main engine tanks following boost, are sufficient to meet APS propellant demands. The booster APS operates in a simple blowdown mode and no additional control is required. Baseline design, operation, and performance characteristics related to orbiter and booster APS are presented in this document.



LOW PRESSURE ORBITER APS INSTALLATION

McDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST

CONTENTS

EFFECTIVE PAGES

1. INTRODUCTION

Auxiliary propulsion will be required for space shuttle attitude and translational control. Operating on the same types of propellant (i.e., oxygen and hydrogen) as the shuttle main propulsion, these subsystems will have a minimum service life of 100 mission cycles without need of major overhaul or refurbishment. Two basic design approaches have been conceived for the APS:

(1) a high pressure concept, using turbopumps or turbocompressors to achieve high operating pressure levels and

(2) a low pressure concept using the main engine propellant tanks as an integral part of the subsystem and operating at main engine tank ullage pressures.

The latter concept was the subject of a seven month study, titled "Space Shuttle Low Pressure Auxiliary Propulsion Subsystem Definition." The study was conducted for the National Aeronautics and Space Administration, Manned Spacecraft Center (MSC), Houston, Texas, under the technical direction of Mr. Norman Chaffee. The study objective was "to conduct preliminary auxiliary propulsion subsystem studies, which would generate information and data, for use in the overall shuttle vehicle effort," and which would, "identify attractive APS concepts, define their range of applicability and limitations and identify critical technology areas and development priorities." The study was performed by McDonnell Douglas Astronautics Company-East (MDAC-East) and its subcontractor Aerojet Liquid Rocket Company under Contract NAS 9-11012. This handbook provides a detailed description of the recommended low pressure APS as defined by that study.

For the orbiter, the preferred approach was identified as one in which an orbit maneuvering subsystem (OMS) performs all high total impulse maneuvers, such as orbit circularization, plane changes, and deorbit functions, while the APS provides all attitude control and vernier maneuvers, such as midcourse corrections and docking. APS velocity increments of approximately 40 ft/sec maximum were determined to be the most favorable allocation of +X axis maneuvers between APS and OMS. The selected APS design uses the main engine tanks as low pressure gas accumulators. Propellants from separate liquid tanks are used for main engine tank resupply. Propellants are first circulated through tubular, passive heat exchangers where they are vaporized and superheated prior to injection into the main engine tanks. During major APS operation, warm propellant vapors from the main engine tanks are mixed with additional liquid propellants in a downstream liquid/vapor mixer and supplied to the engines at constant temperature and pressure (constant density). The booster APS operates entirely on main engine tank propellant residuals in a simple blowdown mode with no additional control required.

This handbook describes the recommended auxiliary propulsion subsystems in sufficient detail for space shuttle definition studies. Included in the description are:

(1) subsystem requirements and constraints,
(2) subsystem operation,
(3) subsystem descriptions (including component identification, usage, and design characteristics),
(4) subsystem performance,
(5) subsystem weights.

2. REQUIREMENTS AND CONSTRAINTS

Auxiliary propulsion subsystem design requirements for both booster and orbiter elements of the space shuttle vehicle were defined in the "Space Shuttle Vehicle Description and Requirements Document (SSVDRD)," Reference (a). Control requirements are provided in Figure 2-1. For design purposes, Reference (a)

VEHICLE ACCELERATIONS		MINIMUM	NOMINAL MIN – MAX	MAXIMUM
(BOOSTER)	TRANSLATION, FT/SEC^2	0.0	0.0 – 0.0	0.0
	PITCH, DEG/SEC^2	0.3	0.5 – 1.0	2.0
	YAW, DEG/SEC^2	0.3	1.0 – 1.75	2.0
	ROLL, DEG/SEC^2	0.3	1.0 – 1.75	2.0
(ORBITER)	TRANSLATION, FT/SEC^2 (+X)	0.5	0.65 – 3.0	7.0
	(OTHER)	0.1	0.2 – 0.5	7.0
	PITCH, DEG/SEC^2	0.5	1.0 – 2.0	4.0
	YAW, DEG/SEC^2	0.9	1.3 – 1.7	4.0
	ROLL, DEG/SEC^2	0.5	1.0 – 2.0	4.0
	REENTRY BANK ANGLE (Y–R), DEG/SEC^2	–	1.5*	–
FAILURE CRITERIA – NOMINAL ACCELERATION WITH ONE (1) ENGINE-OUT – MINIMUM (SAFE) ACCELERATION WITH TWO (2) ENGINES-OUT				

*ALL ENGINES OPERATING

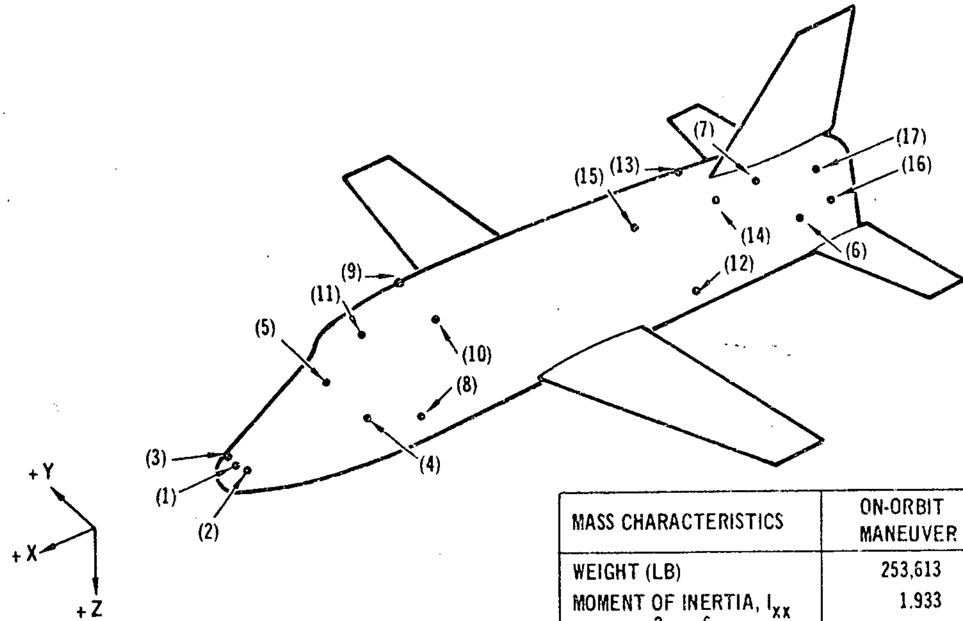
** REFERENCE (a)

VEHICLE REQUIREMENTS** FIGURE 2-1

reliability requirements were interpreted as: fail operational, nominal accelerations shall be achieved with one engine out; and fail safe, minimum acceleration levels shall be achieved with two engines out. The number of engines and thrust level are dictated by these acceleration and reliability requirements, and by the desirability of having all APS engines operate at the same thrust level. Various vehicle installations were synthesized, compared in terms of weight, and from this, final engine arrangements were selected. Orbiter APS impulse requirements are dictated by Reference (a), which defines two basic mission timelines; an early, third orbit, rendezvous and a late, seventeenth orbit, rendezvous.

2.1 Orbiter APS - The orbiter APS performs all attitude control maneuvers, Y and Z axis translation maneuvers, and X axis translation maneuvers $\leq$ 40 ft/sec. The OMS performs all remaining, high total impulse, +X maneuvers, such as orbit circularization, plane changes, and deorbit functions. Optimum impulse allocation between the two subsystems is approximately 3 million lb-sec for the APS and

10 million lb-sec for the OMS. Orbiter APS mission requirements are best satisfied with an engine arrangement employing thirty-three 1080 lb thrust engines. Engine locations are illustrated in Figure 2-2. The selected arrangement, in



MASS CHARACTERISTICS	ON-ORBIT MANEUVER
WEIGHT (LB)	253,613
MOMENT OF INERTIA, I_{xx}	1.933
(SLUG-FT^2 x 10^6) I_{yy}	14.177
I_{zz}	14.559

ORBITER ENGINE ARRANGEMENT

FIGURE 2-2

which all engines are fuselage mounted, results in minimal number of engines, thrust levels, and associated distribution line lengths. Figure 2-3 summarizes the number of engines, their function, and installation data. At the selected thrust level of 1080 lb, six engines are required for +X translation. Eight yaw engines are employed for on-orbit yaw and Y translation; these also provide primary yaw authority during reentry. However, during reentry, the primary yaw engines are backed up by the canted pitch-roll engines, adding additional yaw authority when the error signal between the actual yaw rate and commanded yaw rate exceeds a predetermined value.

Figures 2-4 and 2-5 compare the capability of the selected engine arrangement with requirements given in Figure 2-1. Inspection of the figures shows that all attitude control acceleration and translational acceleration requirements have been achieved. Nominal acceleration levels are provided with one engine out, while minimum (safe) acceleration levels are provided with two engines out. Available reentry bank angle acceleration (not shown) is 1.89 deg/sec^2, which exceeds the nominal minimum requirement of 1.5

LOCATION	MANEUVER	NO. OF ENGINES	ENGINE COORDINATES*			DIRECTION COSINE		
			X	Y	Z	X	Y	Z
1	-X TRANSLATION	1	-260	0	-300	-1.0	0	0
2	-X TRANSLATION	1	-296	-45	-300	-0.926	+0.374	0
3	-X TRANSLATION	1	-296	+45	-300	-0.926	-0.374	0
4	+YAW, +Y TRANSLATION	2	-564	-73	-347	0	+1.0	0
5	-YAW, -Y TRANSLATION	2	-564	+73	-347	0	-1.0	0
6	-YAW, +Y TRANSLATION	2	-1954	-80	-300	0	+1.0	0
7	+YAW, -Y TRANSLATION	2	-1954	+80	-300	0	-1.0	0
8	-PITCH, -ROLL,REENTRY+YAW	2	-653	-135	-203	0	+0.707	+0.707
9	+PITCH, - ROLL,REENTRY-YAW	2	-653	+135	-343	0	-0.707	-0.707
10	+PITCH, + ROLL,REENTRY+YAW	2	-653	-135	-343	0	+0.707	-0.707
11	-PITCH, +ROLL, REENTRY-YAW	2	-653	+135	-203	0	-0.707	+0.707
12	+PITCH,-ROLL, REENTRY-YAW	2	-1865	-110	-195	0	+0.707	+0.707
13	-PITCH,-ROLL, REENTRY+YAW	2	-1865	+110	-405	0	-0.707	-0.707
14	-PITXH,+ROLL, REENTRY-YAW	2	-1865	-110	-405	0	+0.707	-0.707
15	+PITCH,+ROLL, REENTRY+YAW	2	-1865	+110	-195	0	-0.707	+0.707
16	+ X TRANSLATION	3	-2180	-25	-188	+0.993	+0.027	-0.114
17	+ X TRANSLATION	3	-2180	+25	-188	+0.993	-0.027	-0.114

*SEE REFERENCE (a) FOR COORDINATE SYSTEM. ALL DIMENSIONS ARE IN INCHES.

ORBITER ENGINE LOCATIONS
Thirty-Three 1080 Lb Thrust Engines

FIGURE 2-3

AXIS	CONDITION	ON-ORBIT ACCELERATION (DEG/SEC^2)		REENTRY ACCELERATION (DEG/SEC^2)	
		REQUIRED	MIN AVAILABLE	REQUIRED	MIN AVAILABLE
±PITCH	ALL ENGINES OPERATING	-	1.140	-	1.326
	ONE RING OUT	0.50	0.856	1.00	1.00**
	TWO RINGS OUT	0.30	0.570	0.50	0.612
±YAW*	ALL ENGINES OPERATING	-	0.928	-	2.330
	ONE ENGINE OUT	0.50	0.696	1.30	2.052
	(ONE RING OUT) ***			(1.30)	(1.984)
	TWO ENGINES OUT	0.30	0.464	0.90	1.774
	(TWO RINGS OUT) ***			(0.90)	(1.636)
±ROLL	ALL ENGINES OPERATING	-	3.050	-	3.122
	ONE RING OUT	0.50	2.269	1.00	2.322
	TWO RINGS OUT	0.30	1.498	0.50	1.522

* YAW ENGINES BACKED UP BY PITCH-ROLL ENGINES DURING REENTRY
** CRITICAL ACCELERATION
*** REFERS TO PITCH - ROLL ENGINE RINGS USED AS YAW BACKUP DURING REENTRY.

ATTITUDE CONTROL ACCELERATIONS - ORBITER
Thirty-Three 1080 Lb Thrust Engines

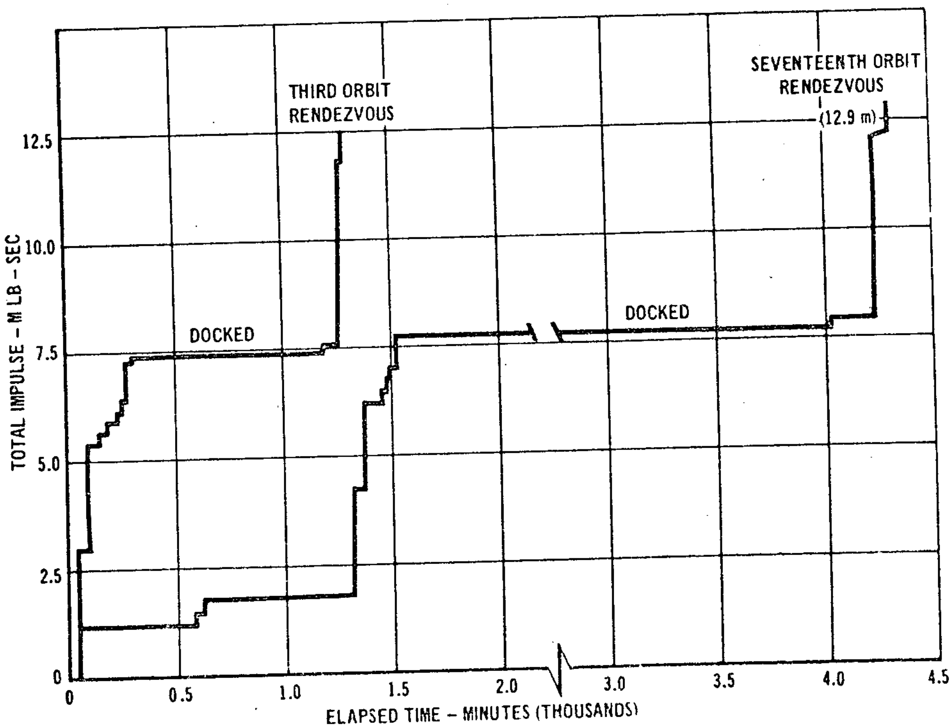
FIGURE 2-4

AXIS	CONDITION	TRANSLATIONAL ACCELERATION (FT/SEC^2) REQUIRED	MIN AVAILABLE
+X	ALL ENGINES OPERATING	-	0.820
	ONE ENGINE OUT	0.65	0.684
	TWO ENGINES OUT	0.50	0.546
−X	ALL ENGINES OPERATING	-	0.381
	ONE ENGINE OUT	0.20	0.254
	TWO ENGINES OUT	0	0.085
±Y	ALL ENGINES OPERATING	-	0.549
	ONE ENGINE OUT	0.20	0.411
	TWO ENGINES OUT	0	0.275
±Z	ALL ENGINES OPERATING	-	0.775
	ONE ENGINE OUT	0.20	0.582
	TWO ENGINES OUT	0	0.388

TRANSLATIONAL ACCELERATIONS – ORBITER
Thirty-Three 1080 Lb Thrust Engines

FIGURE 2-5

Orbiter APS total impulse requirements and impulse expenditure history were defined for the mission timelines of Reference (a). Results are shown in Figure 2-6 for the third and seventeenth orbit rendezvous missions; total impulse

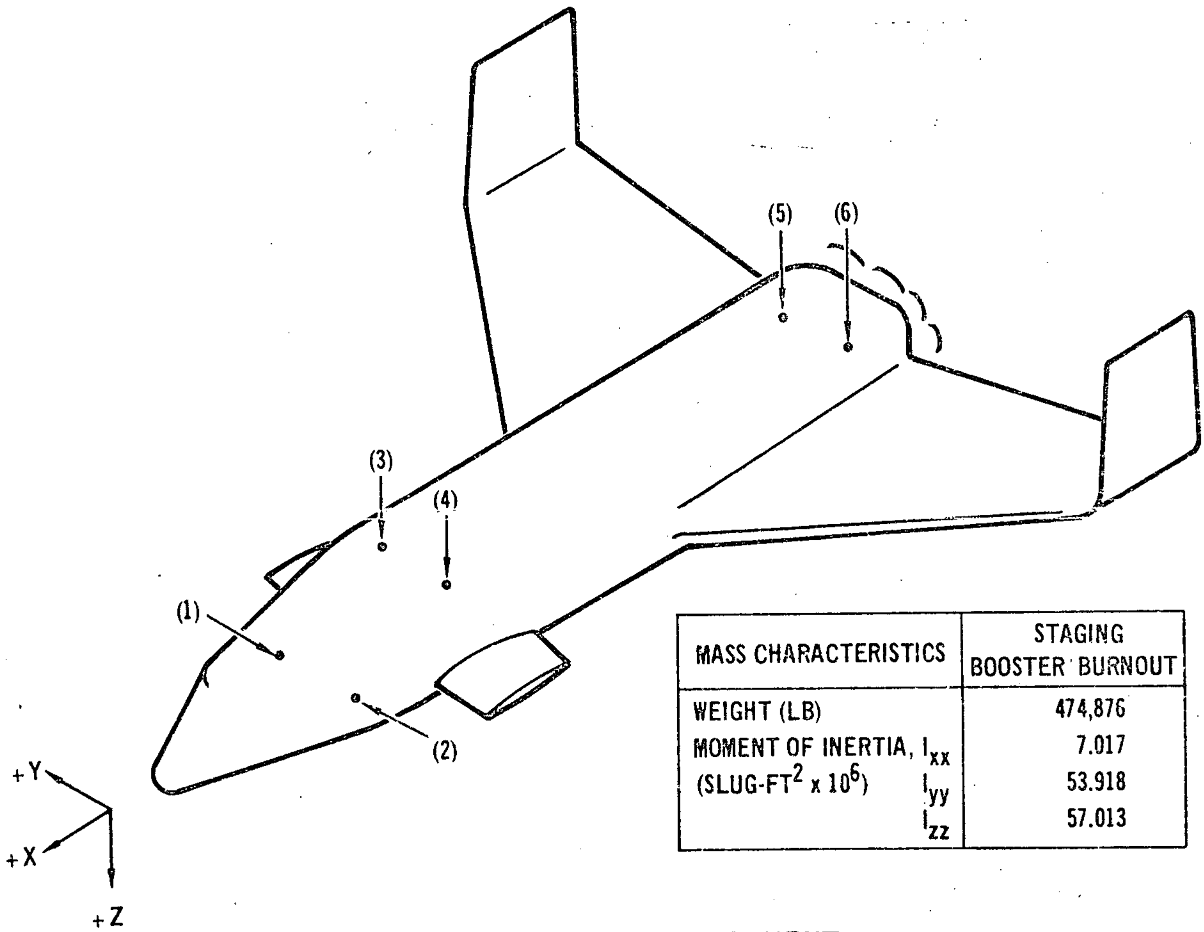


ORBITER IMPULSE TIME HISTORY
(SPACE STATION/BASE LOGISTICS MISSION)

FIGURE 2-6

requirements are 12.5 and 12.9 million lb-sec, respectively. The orbiter APS was designed to meet the most critical mission duty cycle, the seventeenth orbit rendezvous.

2.2 Booster APS - The booster APS acceleration requirements (Figure 2-1) are met with twenty, 2500 lb thrust engines. The engine arrangement consists of eight yaw engines and twelve pitch-roll engines (illustrated in Figure 2-7).



MASS CHARACTERISTICS	STAGING BOOSTER BURNOUT
WEIGHT (LB)	474,876
MOMENT OF INERTIA, I_{xx}	7.017
(SLUG-FT^2 x 10^6) I_{yy}	53.918
I_{zz}	57.013

BOOSTER ENGINE ARRANGEMENT

FIGURE 2-7

These engine locations were selected to minimize subsystem weight. Engine location, function, and installation data are tabulated in Figure 2-8 for each engine group shown in Figure 2-7. Figure 2-9 compares control acceleration requirements from Reference (a) with subsystem performance capabilities. As this figure shows, selected booster APS performance capabilities satisfy all Reference (a) attitude control maneuver requirements, including all failure mode conditions.

LOCATION	MANEUVER	NUMBER OF ENGINES	ENGINE COORDINATES*			DIRECTION COSINE		
			X	Y	Z	X	Y	Z
1	– YAW	4	–425	+93.5	–13	0	–1	0
2	+ YAW	4	–425	–93.5	–13	0	+ 1	0
3	– PITCH, + ROLL	3	–1120	+151	–149	0	–0.309	+0.95
4	– PITCH, – ROLL	3	–1120	–151	–149	0	+ 0.309	+0.95
5	+ PITCH, + ROLL	3	–2569	+151	–149	0	0	+1
6	+ PITCH, – ROLL	3	–2569	–151	–149	0	0	+1

*SEE REFERENCE (a) FOR COORDINATE SYSTEM. ALL DIMENSIONS ARE IN INCHES.

BOOSTER ENGINE LOCATIONS
Twenty 2500 Lb Thrust Engines

FIGURE 2-8

AXIS	CONDITION	ACCELERATION (DEG/SEC^2)	
		REQUIRED	MIN AVAILABLE
+ PITCH	ALL ENGINES OPERATING	–	0.744
	ONE ENGINE OUT	0.50	0.620
	TWO ENGINES OUT	0.30	0.495
– PITCH	ALL ENGINES OPERATING	–	1.120
	ONE ENGINE OUT	0.50	0.935
	TWO ENGINES OUT	0.30	0.747
± YAW	ALL ENGINES OPERATING	–	1.321
	ONE ENGINE OUT	1.00	1.00*
	TWO ENGINES OUT	0.30	0.661
± ROLL	ALL ENGINES OPERATING	–	1.285
	ONE ENGINE OUT	1.00	1.028
	TWO ENGINES OUT	0.30	0.771

* CRITICAL ACCELERATION

ATTITUDE CONTROL ACCELERATIONS – BOOSTER
Twenty 2500 Lb Thrust Engines

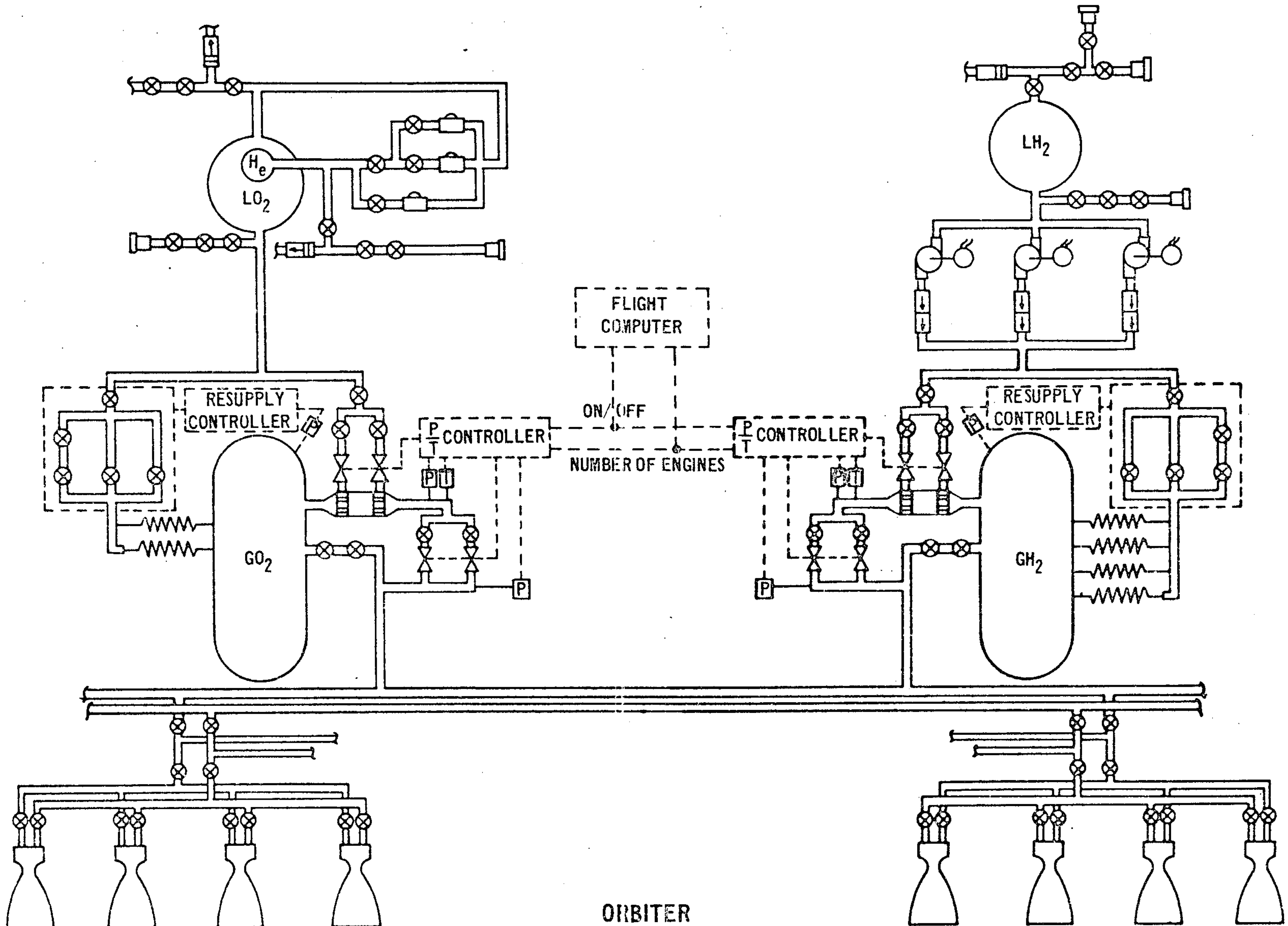
FIGURE 2-9

3. SUBSYSTEM OPERATION

3.1 APS Operation (Orbiter) - The orbiter low pressure APS uses thirty-three 1080 lb thrust engines. Main engine tanks are used as gas accumulators, operating over a pressure range of 16 to 30 lbf/in^2a. When the ratio of tank vapor pressure to temperature (P/T) decays below a predefined value of 0.0566 (30/530 $lbf/in^2a/°R$), additional propellant is resupplied from a liquid storage assembly. Resupply propellant is vaporized and superheated by passive heat exchangers before injection into main engine tanks. During major APS operations, warm propellant vapors from the main engine tanks are mixed with liquid propellant in a downstream mixing chamber, then supplied to the engines at constant temperature and pressure. In case of engine failure, the faulty engine (or group of engines) is isolated to provide nominal acceleration levels after the first failure and minimal acceleration after the second. The subsystem schematic is shown in Figure 3-1.

The orbiter APS operational mode is dependent upon propellant usage demands. The subsystem operates entirely from main engine tank propellant vapors during periods of low APS demands, and no control of engine inlet conditions is required. During a major APS burn, however, only a portion of the propellant is extracted from the tanks; the remainder being supplied as liquid to a mixing assembly where liquids and vapors are mixed to achieve a constant outlet propellant temperature for supply to the APS engines. During both modes of operation, propellants from the liquid storage tanks are supplied to the main engine tanks, via a passive heat exchanger assembly; resupply fluid flow rates are controlled to match flow rates out of the tank.

Low pressure APS mission operation follows the sequence presented below. At the end of boost, liquid and gaseous propellants are trapped in the main engine tanks and feedlines. Environmental heating of the tanks warms the propellant vapor and boils off the liquid residual. If heating is sufficient to reach tank relief pressure of 30 lbf/in^2a, venting occurs and propellant is lost. APS operation during this initial phase decreases tank pressure and precludes propellant venting. Thus, during the early mission phases, the APS operates almost entirely from residual propellant contained within main engine tanks. As the mission proceeds, tank pressure decays and propellant must be resupplied from the liquid propellant storage assembly. The resupply propellant is vaporized and superheated in the passive heat exchanger, mounted to the main engine tank. Main engine tanks thus

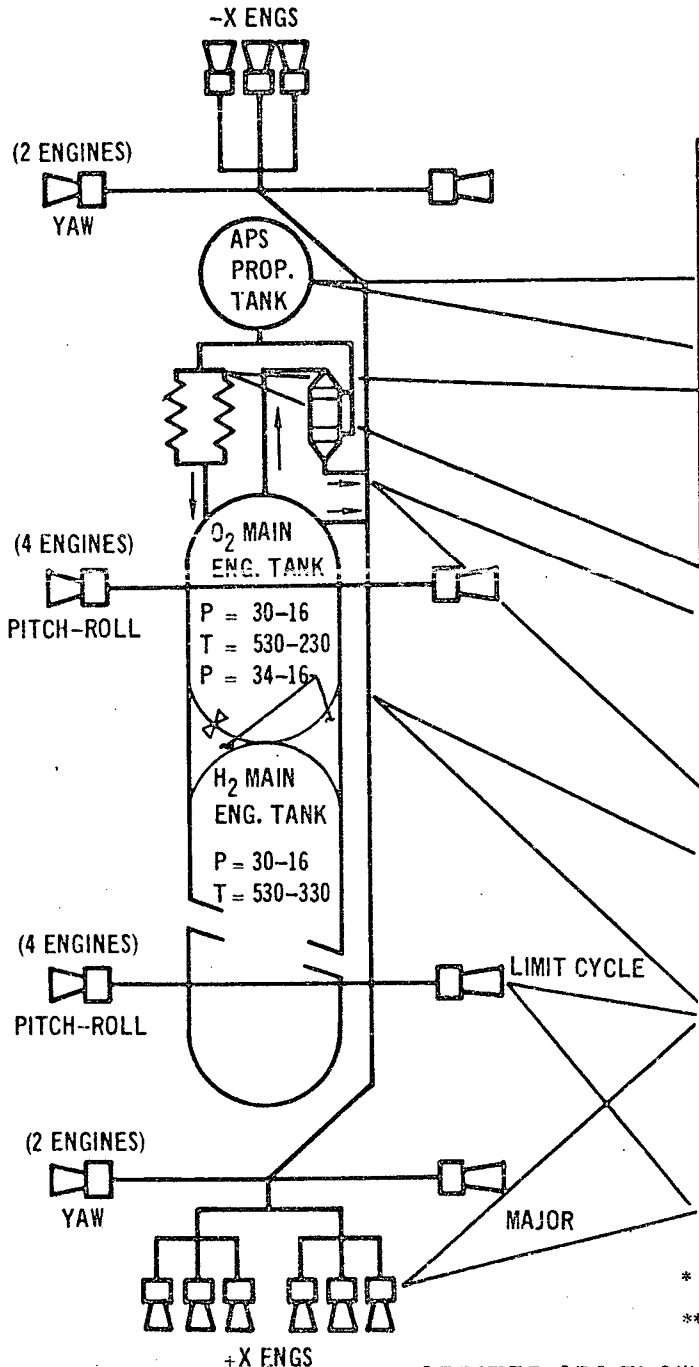


ORBITER
BASELINE AUXILIARY PROPULSION SUBSYSTEM

FIGURE 3-1

serve both as heat sources (to condition the propellant) and as accumulators (to store the propellant vapor).

During low demand and initial phase APS operation, engine inlet conditions vary, since all propellant is extracted from the main engine tank. Pressure, temperature, and flow balances are given in schematic Figure 3-2 for typical limit



APS OPERATION*				
ITEM	MAJOR		LIMIT CYCLE**	
	O_2	H_2	O_2	H_2
APS PROPELLANT TANKS				
P	35	40–18	35	40 – 18
T	163	37.5	163	37.5
HEAT EXCHANGER				
P_{IN}	35	57–35	35	57 – 35
P_{OUT}	30–28	47–25	34	56 – 34
T_{IN}	163	37.5	163	37.5
T_{OUT}	400–280	450–250	440–280	450–280
$\dot{\omega}$	6.0	1.0		
LIQUID/VAPOR MIXER				
P_{IN}	35	57–35	–	–
P_{OUT}	20	20	30–16	30–17
T_{IN}	163	37.5	–	–
T_{OUT}	200	150	530–230	530–330
$\dot{\omega}$	8–6	2.7–2.4	13.2–8.0	4.0–3.2
MAIN SUPPLY LINES				
T	200	150	530–230	530–330
$\dot{\omega}$	13.0	4.3	6.6–4.0	2.0–1.6
M	0.181	0.194	0.100–0.080	0.123–0.157
ENGINE ASSEMBLIES (TYP)				
F	1080		1500– 950	
P_c	13.7		16.0–13.7	
P_{INJ}	15.7	15.7	28 – 16	28–16
T_{INJ}	200	150	530–230	530–330
$\dot{\omega}_{INJ}$	2.16	0.72	3.3–2.0	1.0– 0.8

* UNITS ARE P = LBF/IN^2 A, T = $^\circ$R, F = LB, $\dot{\omega}$ = LB/SEC
** LIMIT CYCLE VALUES ARE AVERAGE.

ORBITER APS FLOW BALANCES

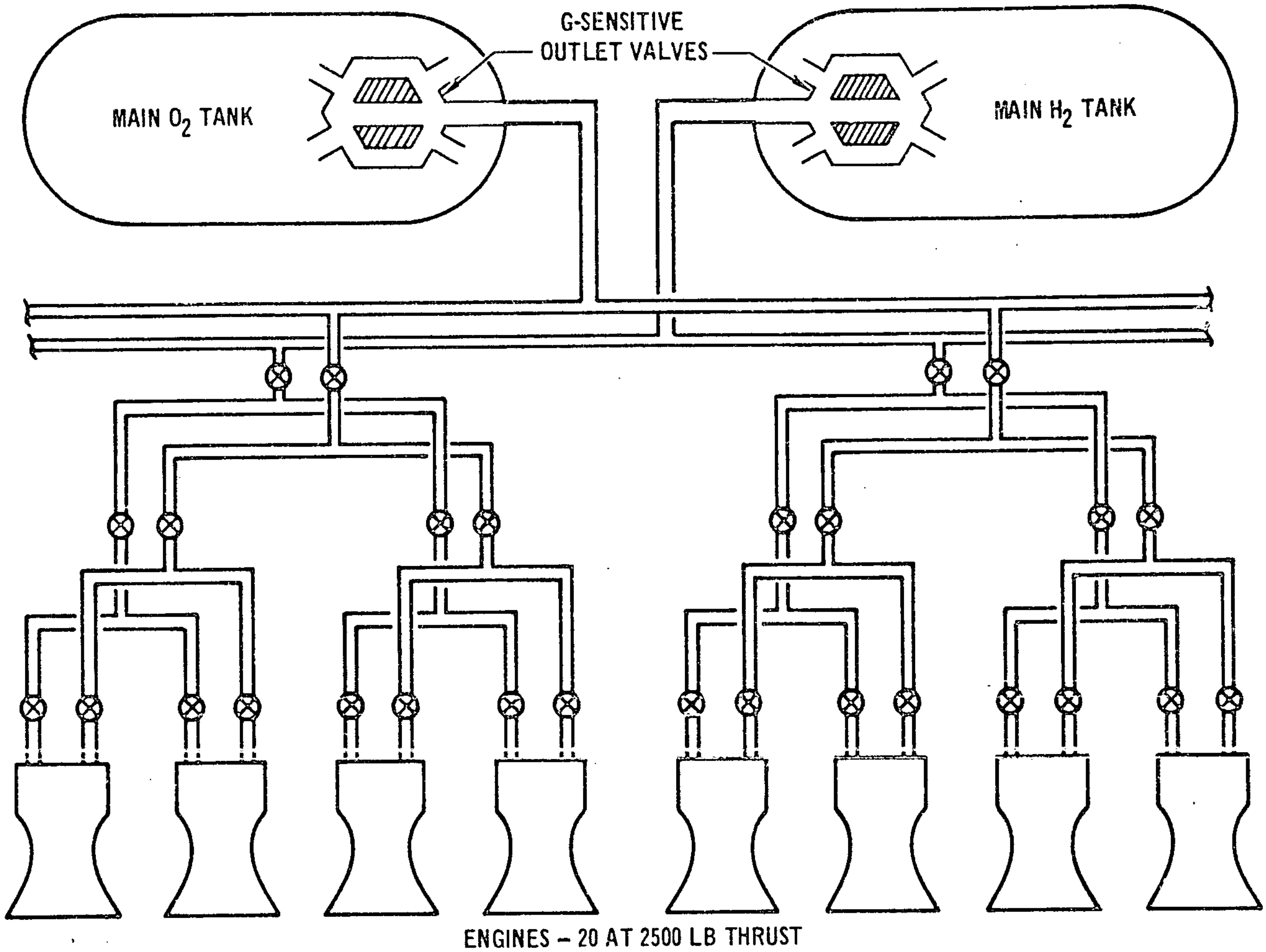
FIGURE 3-2

cycle operation. When a major APS operation is scheduled, however, engine inlet conditions are closely controlled by addition of liquid propellant (taken from the APS storage assembly) to the mixer assembly. Pressures, temperatures, and flow rates for this mode of operation are also shown in Figure 3-2.

After each major APS operation, propellant vapor in the main engine tank will be relatively cool, and tank walls will be chilled because of heat removal for propellant conditioning. Normal radiation from the vehicle skin to the tank walls will restore tank wall temperature; heat transfer, from the tank walls to the gas inside, will raise gas temperature and pressure to their original condition and will prepare the APS for its next major demand.

3.2 APS Operation (Booster) - The booster low pressure APS operates in a blowdown mode, utilizing main engine tank residual propellants. At main engine cutoff, the main engine tanks and feedlines contain sufficient liquid and gaseous propellant residuals to satisfy the entire APS mission duty cycle. Hence, the booster APS requires no additional tankage, thermal conditioning, or liquid/vapor mixing assemblies. The complete APS consists of a propellant distribution assembly and control engine assemblies, both shown schematically in Figure 3-3. The design uses twenty 2500 lb thrust engines.

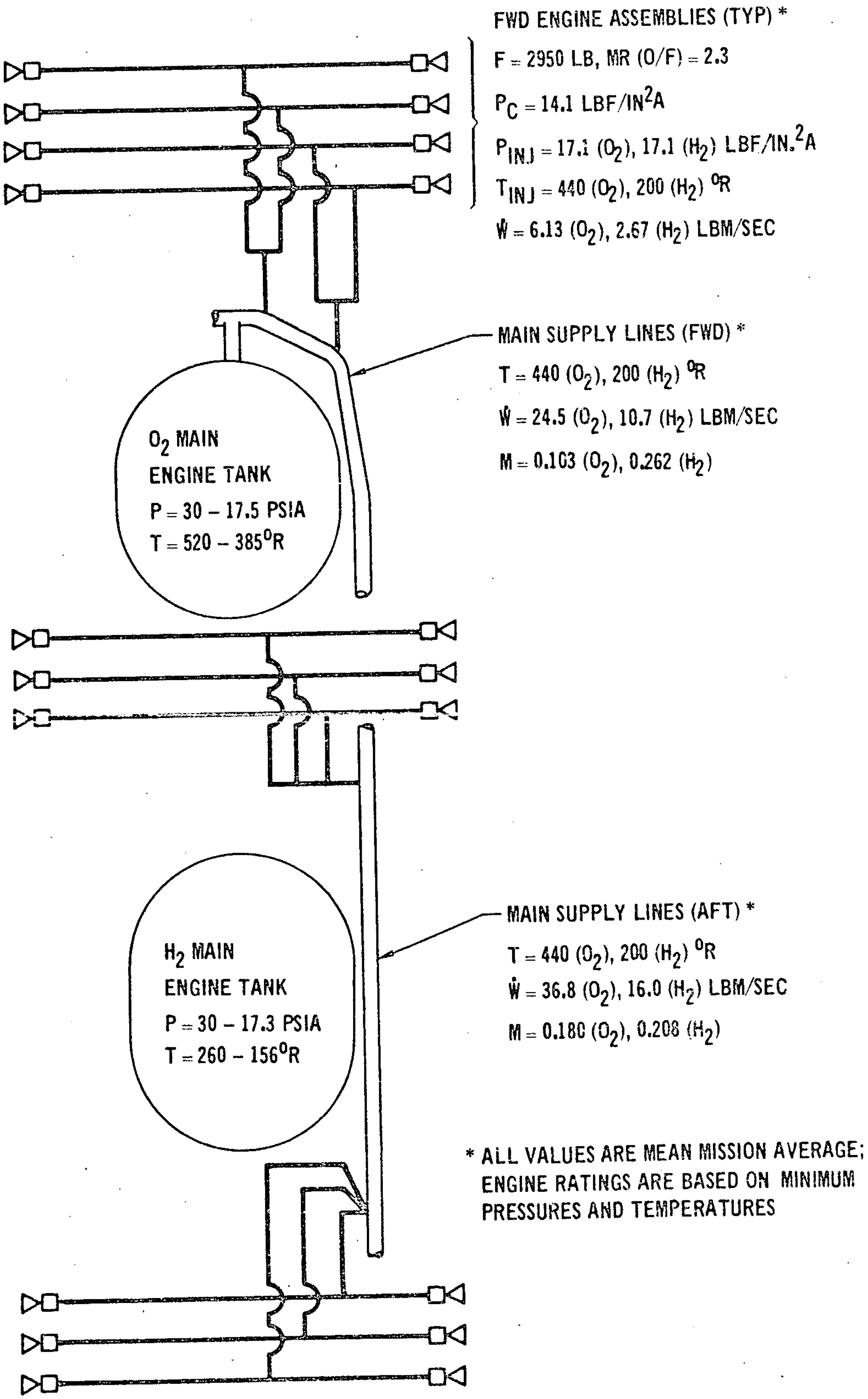
Initial booster residuals, as specified by Reference (a), were at vapor pressures of 26 lbf/in^2a and vapor temperatures of 450°R (H_2) and 520°R (O_2). These high pressurant temperatures created a severe subsystem weight penalty due to reduced propellant density. At this lower initial density, the amount of pressure decay is increased and design pressure of lines and engines is reduced. This, of course, results in increased line and engine size and weight. Minimum main engine tank pressures during APS usage and resultant APS weights were determined as a function of initial vapor temperature and APS mixture ratio. This analysis demonstrated that Reference (a) propellant conditions would unnecessarily penalize the low pressure APS. For this reason, the initial hydrogen tank vapor temperature was reduced from 450°R to 260°R and the increased vapor residual associated with this temperature reduction was assessed against the APS as a weight penalty. No temperature reductions were necessary for the oxygen tank. These temperatures constrain operating tank pressures to a minimum of 17 lbf/in^2a.



BOOSTER BASELINE AUXILIARY PROPULSION SUBSYSTEM

FIGURE 3-3

When APS engines are fired, propellant vapor is extracted from main engine tanks and pressure within these tanks decays. The thermodynamic process corresponding to this operation is similar to that for any gas storage bottle blowdown. For low flow rates, pressure decay is nearly isothermal; however, if outflow rate is high, the process is more nearly isentropic. Following engine shutdown, pressure and temperature profiles are dependent on heat transfer into the system. Figure 3-4 presents a schematic of the booster APS, showing ranges of pressure, temperatures, and flow rates experienced during operation. The booster main engine tank pressures fluctuate from 26 to 17 lbf/in^{2}a and engine inlet temperatures vary from 520° to 385°R for oxygen and 260° to 156°R for hydrogen.



BOOSTER APS FLOW BALANCES

FIGURE 3–4

4. SUBSYSTEM DESCRIPTION

4.1 Equipment Design and Operation (Orbiter) - The orbiter low pressure auxiliary propulsion subsystem contains five primary assemblies:

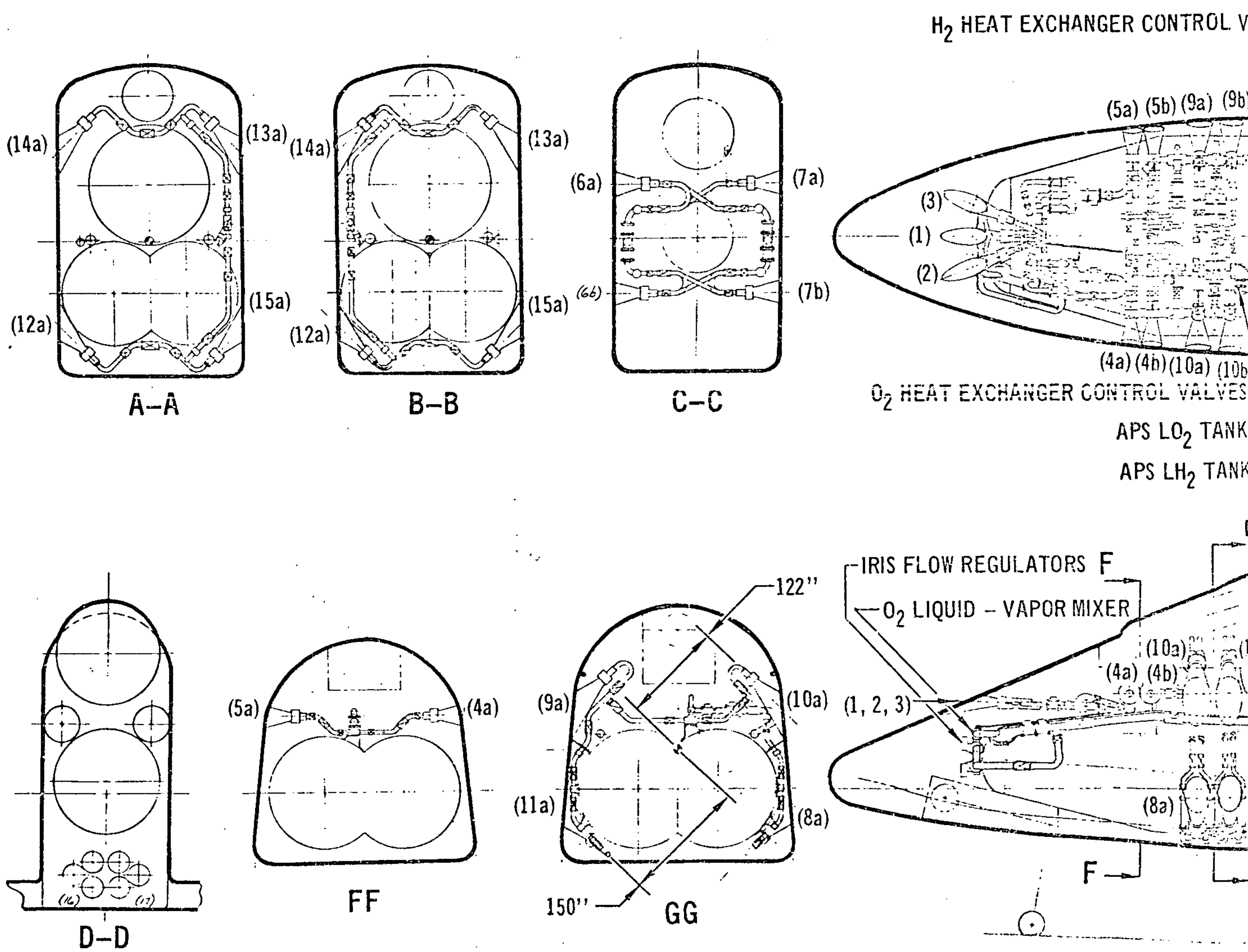
(1) propellant storage assembly, consisting of liquid propellant storage tanks and associated thermal protection, propellant positioning, and pressurization subassemblies
(2) propellant conditioning assembly, consisting of main engine tanks with an integral passive heat exchanger
(3) liquid/vapor mixing assembly, consisting of a liquid injection/mixing chamber and constant density controls
(4) propellant distribution assembly and associated valves and controls
(5) engine assemblies

The main engine propellant tanks are also an integral part of the APS, serving primarily as gas accumulators, and secondarily as mixing chambers and heat sources. These assemblies are described below. Equipment locations within the orbiter are shown in Figure 4-1 and the orbiter APS design summary is presented in Figure 4-2.

Propellant Storage Assembly (Orbiter) - The APS storage assembly contains sufficient propellant for approximately 3 million lb-sec of impulse. Dedicated (separate) propellant storage tanks are provided for the APS and OMS. Storage assembly tankage requirements for the APS are:

	H_2		O_2
Usable Propellant Weight, lb	2351		4398
Ullage Allowance, Percent	10		5
Tank Design Pressure, lbf/in^{2}a	40		35
Maximum Acceleration, ft/sec^2			
On Orbit (+X Axis)		2	
Entry (+Z Axis)		71.3	

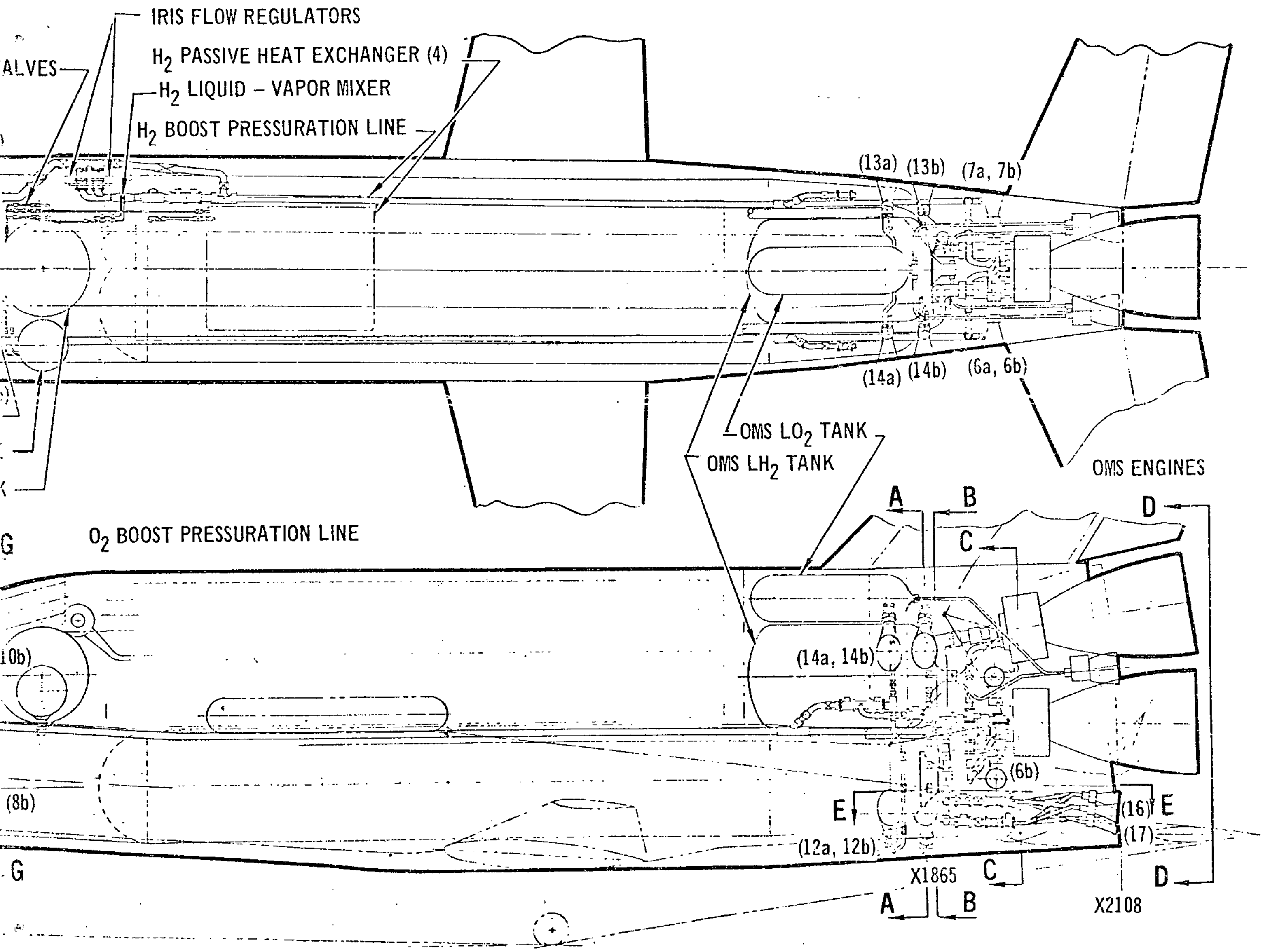
Oxygen and hydrogen propellant tank designs are similar except for pressurization subassemblies. A regulated, cold helium supply is used for liquid oxygen pressurization and submerged, low suction head pumps are used for liquid hydrogen. The liquid hydrogen tank, shown in Figure 4-3, consists of a 2219-T87 aluminum



4-1-a

FOLDOUT FRAME 1

INSTALLATION – LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM – ORBITER



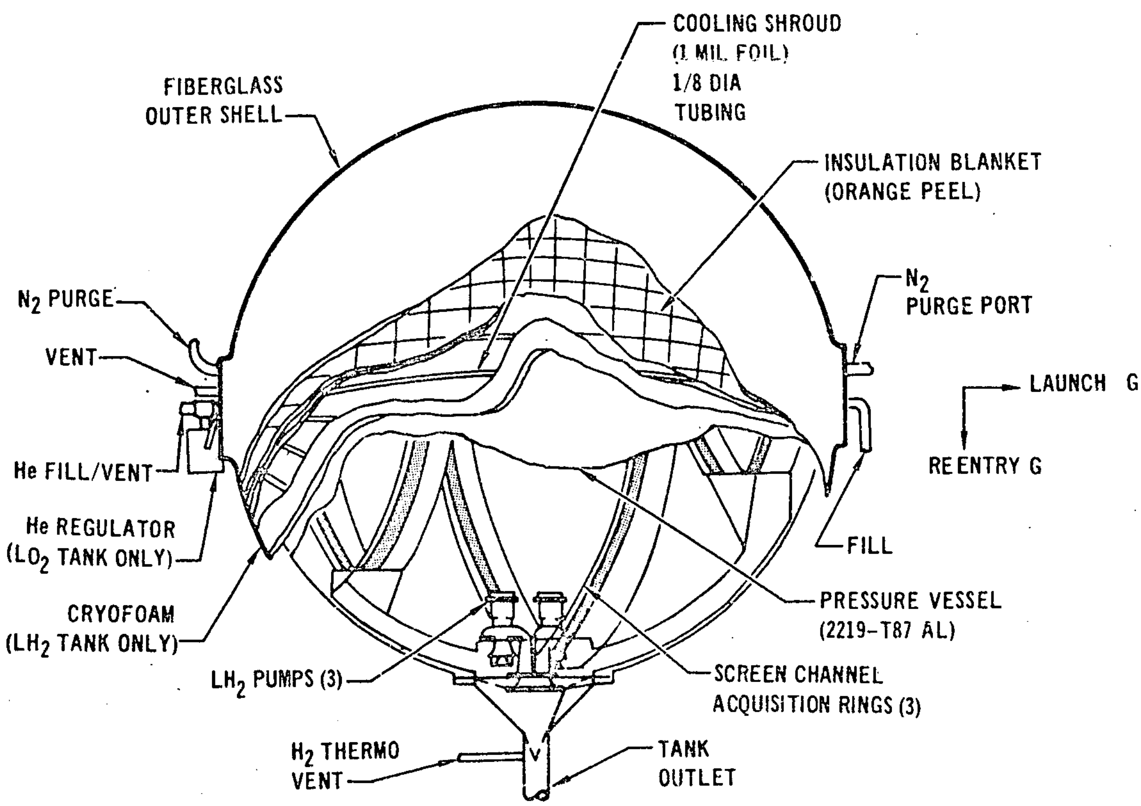
FOLDOUT FRAME 2

FIGURE 4–1

	O_2	H_2
LIQUID STORAGE AND PRESSURIZATION ASSEMBLY		
PROPELLANT WEIGHT, LB	4496	2499
PROPELLANT TANK PRESSURE, LBF/IN^2A	35	40
PROPELLANT TANK VOLUME, FT_3	67	634
PRESSURIZATION TYPE	COLD H_e	PUMP
PROPELLANT SUPPLY PRESSURE, LBF/IN^2A	35	35
HEAT EXCHANGER		
AREA, FT^2	1,790	3,100
TUBE LENGTH, FT	17.5	15.0
TUBE SPACING	4.0	10.0
TUBE DIAMETER, IN.	0.394	0.298
NUMBER OF TUBES	308	248
LIQUID-VAPOR MIXER		
OUTLET TEMPERATURE, °R	200	150
INJECTOR INLET PRESSURE, LBF/IN^2A	30	30
LIQUID THROTTLE RATIO	10:1	10:1
GAS-SIDE PRESSURE DROP, LBF/IN^2D	1.0	1.5
ENGINE AND DISTRIBUTION ASSEMBLIES		
DESIGN REGULATED PRESSURE, LBF/IN^2A	20	20
MAXIMUM LINE DIAMETER, IN.	8.3	8.3
ENGINE INLET PRESSURE, LBF/IN^2A	15.7	15.7
ENGINE THRUST, LB	1,080	
CHAMBER PRESSURE, LBF/IN^2A	13.7	
MIXTURE RATIO	3:1	
EXPANSION RATIO	8:1	

ORBITER BASELINE DESIGN SUMMARY

FIGURE 4-2



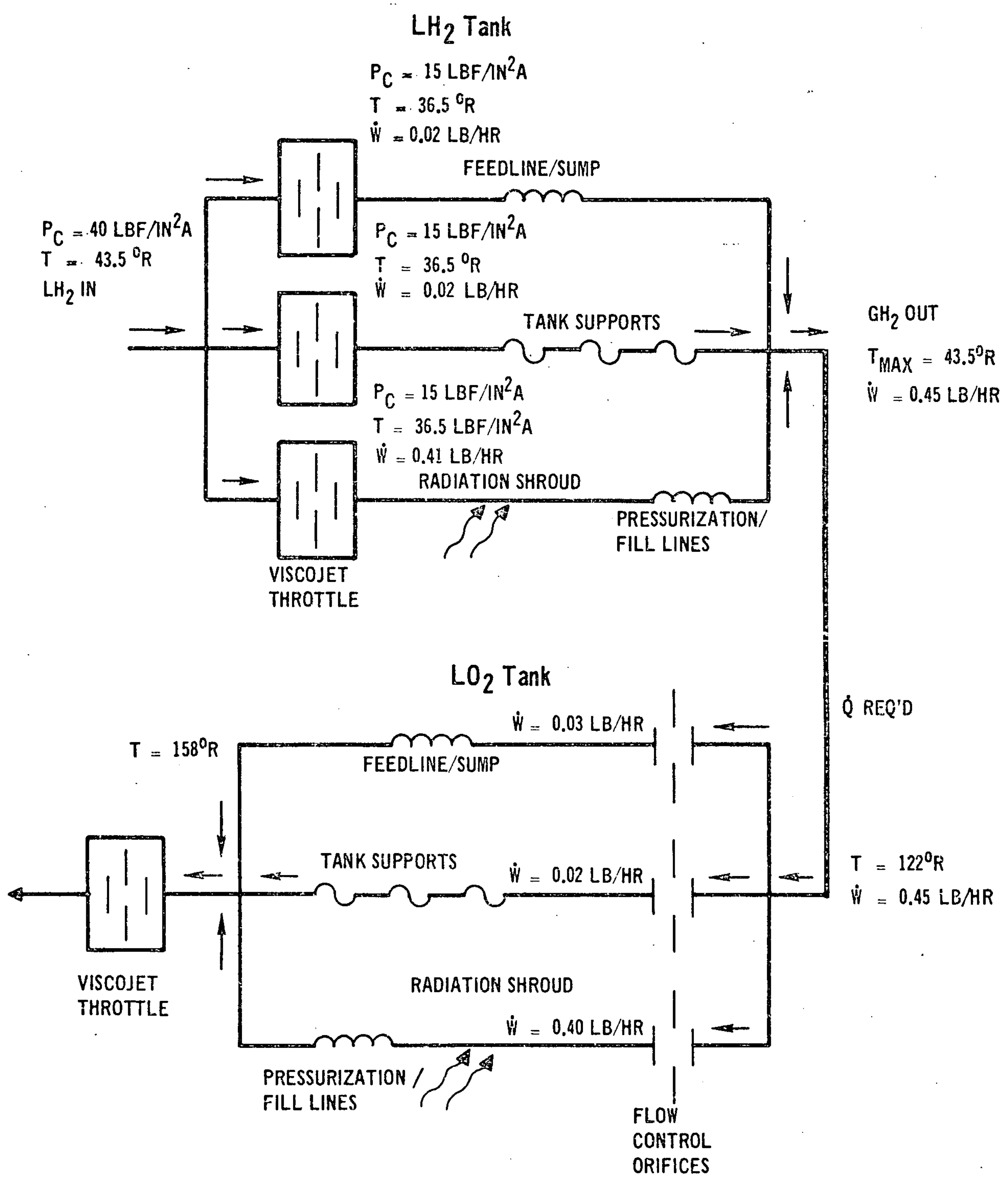
PROPELLANT TANK INSULATION/COOLING DESIGN

FIGURE 4-3

structural shell (or pressure vessel), insulation, and protective covering. The insulation subassembly is comprised of a 0.4 in. polyurethane substrate over the structural shell to prevent cryopumping during ground purge (with nitrogen), a cooling shroud to intercept heat leaks from tank supports and surroundings, and an aluminized Mylar, multilayer insulation shield for space operation. The cooling shroud, is a 1 mil aluminum foil dip-brazed to a coil of 1/8 in. aluminum tubing. A small quantity of liquid hydrogen, which is extracted from the storage tank, is circulated through the coil where it absorbs incoming heat through vaporization. Figure 4-4 is a schematic of the vent design, showing temperature, pressure and flow balances of the hydrogen coolant. The hydrogen is extracted from the propellant acquisition device, throttled to reduce its temperature, and passed through the tank insulation cooling shrouds (first the H_2 and then the O_2) prior to being vented overboard. A temperature drop of 7°R across the throttle valve provides a good balance between the number of coils for feed line/pump cooling and reasonable tube size for the insulation cooling heat exchanger. Tank insulation is fabricated of gore segments laced together with Nomex thread, as shown in Figure 4-5. The insulation is protected from structural damage and atmospheric moisture degradation by a fiberglass outer jacket. During boost and entry, the outer shell is pressurized with nitrogen to prevent collapse pressure loads. After boost, the nitrogen is vacuum vented to achieve the low heat transfer rates associated with evacuated insulation layers. The oxygen tank is identical, except that the polyurethane foam substrate is not required.

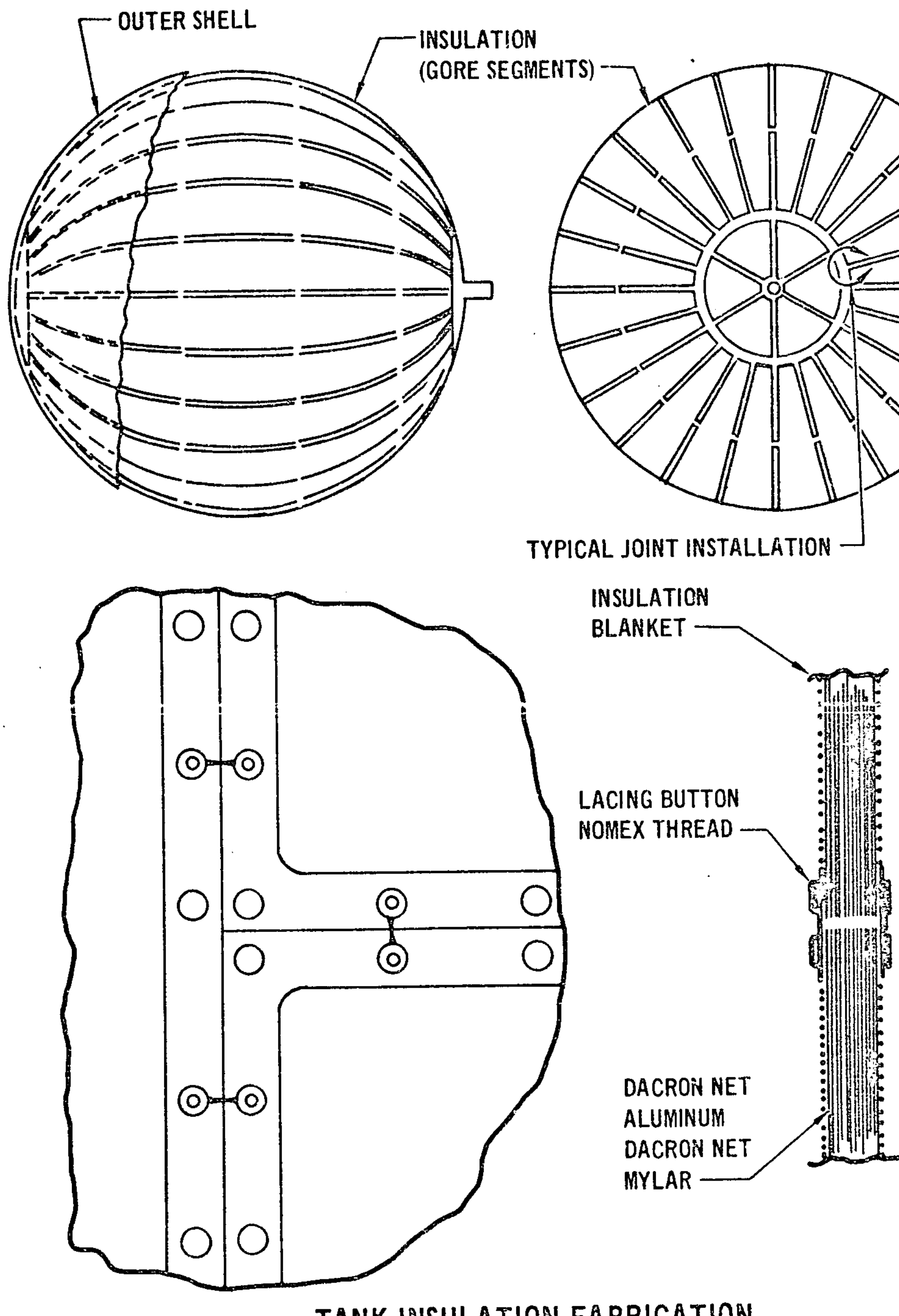
Both hydrogen and oxygen tanks incorporate a surface tension screen device for propellant acquisition. The surface tension device is made up of three annular trays, as shown in Figure 4-6. The annular trays are separated from the tank walls to prevent heat leak and subsequent propellant vaporization within the acquisition device, but are sufficiently close to the wall to allow contact with liquid for any propellant orientation. Each tray consists of an aluminum channel covered by a perforated plate, which serves as a screen support and adds to rigidity. Figure 4-7 shows the design concept. Screen design and launch orientation facilitate bubble point tests between flights. The tank outlet location provides normal gravity outflow during entry, with associated high expulsion efficiency.

Oxygen tank pressurization is accomplished by a conventional cold helium pressurization assembly. A high pressure (3000 lbf/in^2a) stainless steel helium storage tank is mounted inside the liquid oxygen tank. Regulators maintain tank



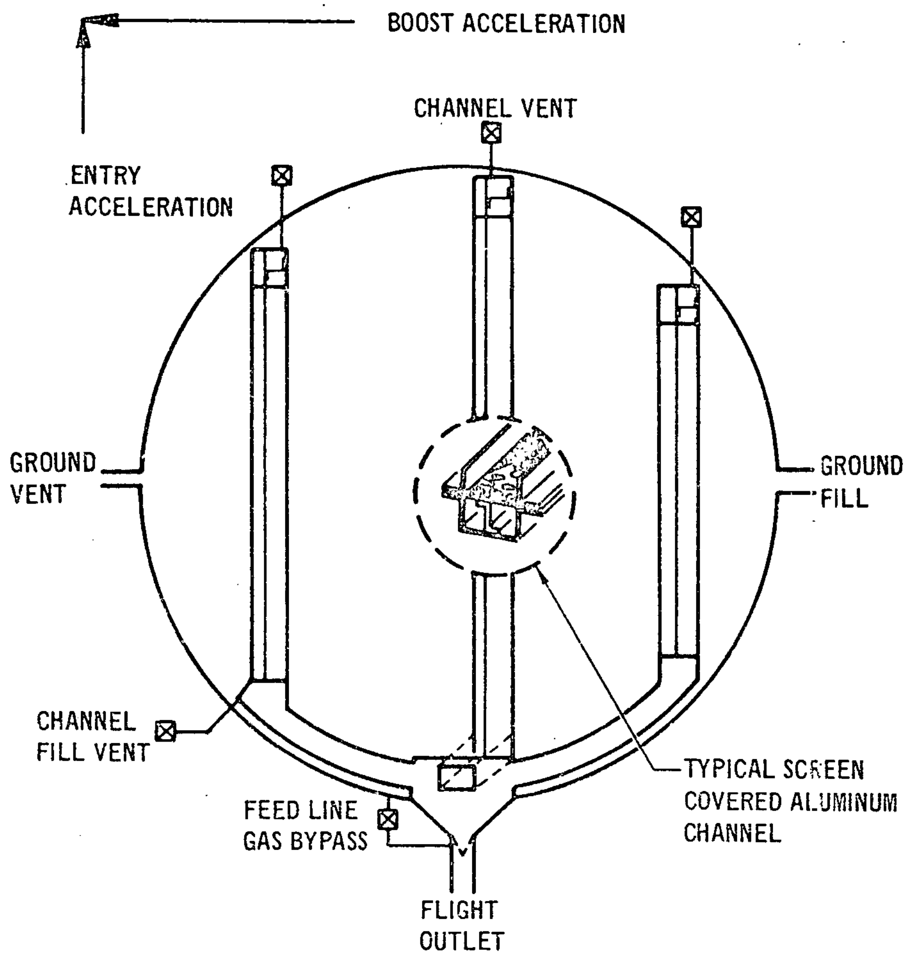
VENT SYSTEM SCHEMATIC

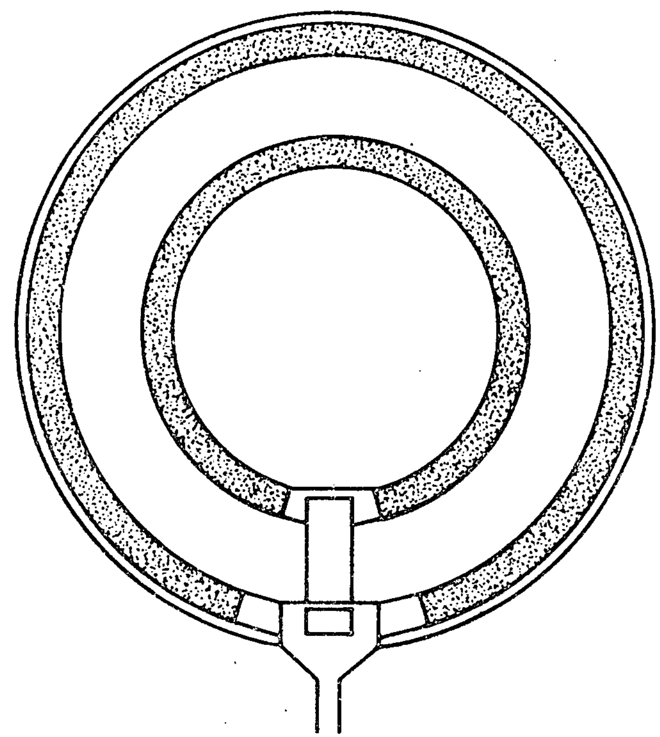
FIGURE 4-4



TANK INSULATION FABRICATION

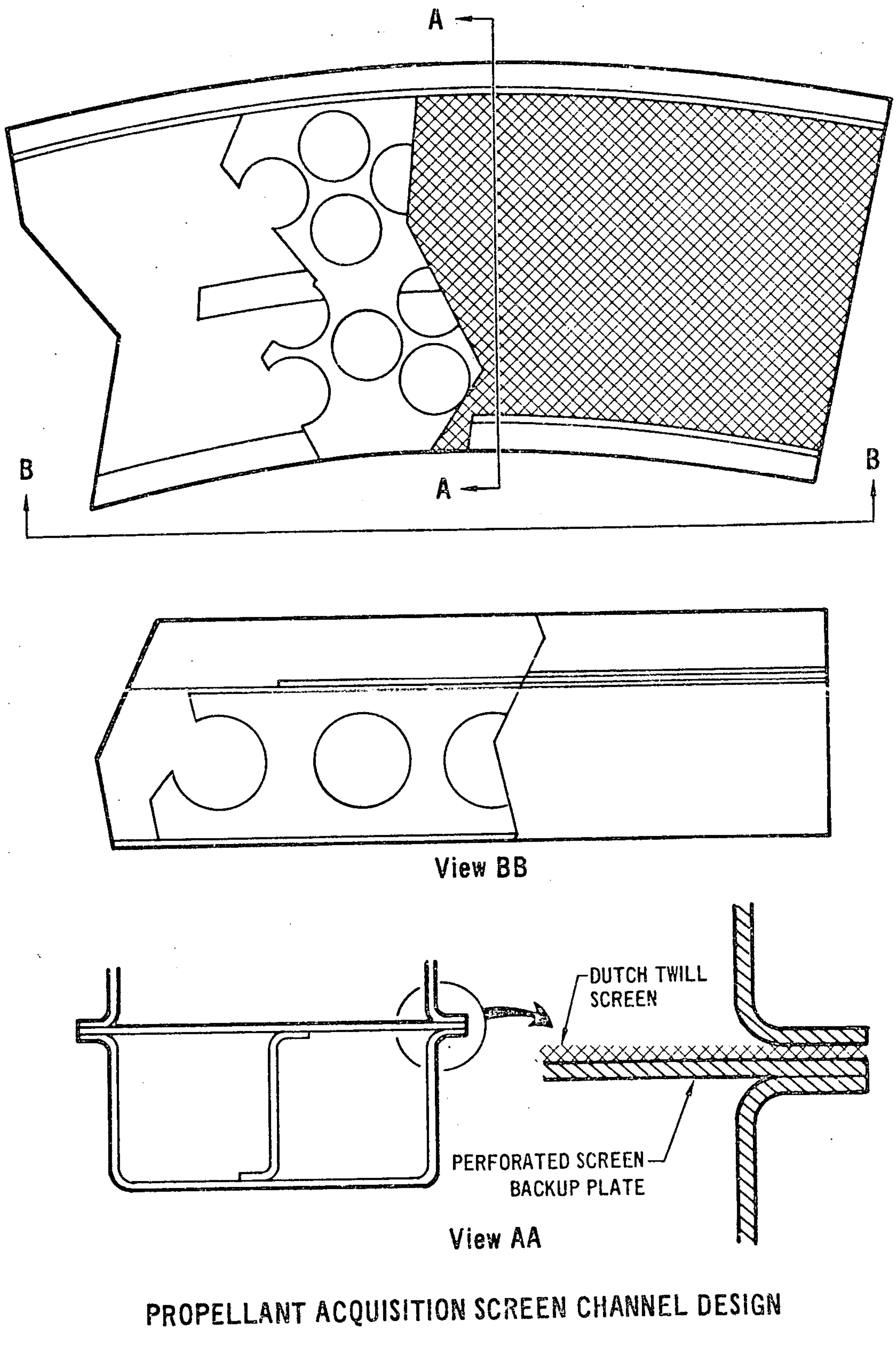
FIGURE 4-5





PROPELLANT	SCREEN SIZE	CHANNEL SIZE (IN)
O_2	250 x 1370 (17μ) 200 x 600 (40μ)	3 x 6
H_2	325 x 2300 (10μ) 200 x 600 (40μ)	5 x 8

FIGURE 4-6



PROPELLANT ACQUISITION SCREEN CHANNEL DESIGN

FIGURE 4-7

	OXYGEN	HYDROGEN
PRESSURIZATION		
TYPE	COLD HELIUM	PUMP
STORAGE PRESSURE, LBF/IN^2A	3000	(40 HE PREPRESS)
STORAGE TEMPERATURE, ^oR	165	-
SUPPLY PRESSURE, $LBF/IN.^2A$	35	35 MIN
PUMP HORSEPOWER, BHP	-	6.1
ELECTRICAL POWER	-	208V (23 AMPS)
PROPELLANT TANK		
VOLUME, FT^3	67	634
DESIGN PRESSURE, $LBF/IN.^2A$	35	40
MATERIAL	2219-T87 AL	2219-T87 AL
INSULATION	HPI	HPI/CRYOFOAM
THICKNESS, IN.	0.97	0.68 (HPI)/0.42 (FOAM)
COOLING	H_2VENT	H_2VENT
VENT RATE, LB/HR	-	0.45
SHROUD	1 MIL AL FOIL	1 MIL AL FOIL
TUBING	1/8 DIA;0.010 WALL	1/8 DIA; 0.010 WALL
PROPELLANT ACQUISITION	SCREEN TRAP	SCREEN TRAP
EXTRACTION RATE, GPM	103	550
HYDROSTATIC HEAD, LBF/FT^2	41	6.4
EXPULSION EFFICIENCY	0.987	0.991

APS PROPELLANT STORAGE DESIGN SUMMARY

FIGURE 4-8

pressure to 35 lbf/in^2a. Hydrogen pressurization requirements are satisfied by low head rise, motor driven boost pumps submerged in the hydrogen tank outlet. Pump design characteristics are:

head rise, lbf/in^2	17
flow rate, gpm	370
diameter, in.	8
speed, rpm	11,400
power, hp	6.1
weight, lb	24.2

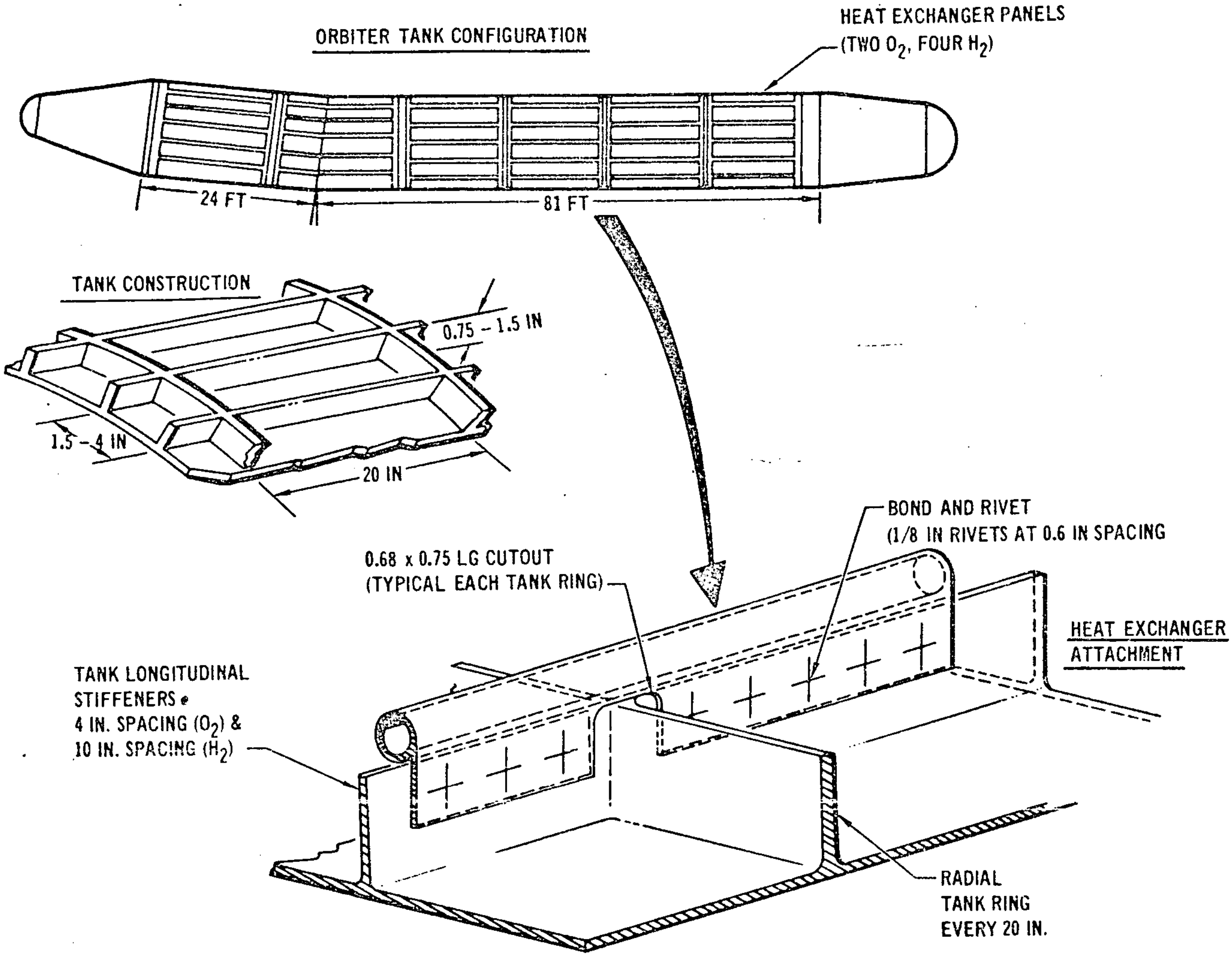
The tank is prepressurized to 40 lbf/in^2a with helium to prevent nucleate boiling. During APS operation, tank pressure decays from 40 to 18 lbf/in^2a. Correspondingly, pump outlet pressures decay from 57 to 35 lbf/in^2a.

Pertinent physical and performance characteristics of the propellant storage assembly are summarized in Figure 4-8. Hydrogen and oxygen storage assembly weights are 820 and 233 lb, respectively. A weight breakdown is shown in Figure 4-9.

	HYDROGEN (LB)	OXYGEN (LB)
STRUCTURAL COMPONENTS		
PROPELLANT TANK	224	51
FIBERGLASS SHELL (INCLUDING SUPPORTS)	98	22
PROPELLANT ACQUISITION DEVICE	105	37
TANK MOUNTS	62	50
TANK INSULATION		
FOAM SUBSTRATE	31	-
INSULATION BLANKET	99	32
INSULATION SUPPORTS	10	3
COOLANT LOOP		
SHROUD	28	2
VALVES, CONTROLS	4	4
PRESSURIZATION	159	32
TOTAL	820	233

PROPELLANT STORAGE ASSEMBLY – TANK WEIGHT SUMMARY FIGURE 4-9

Propellant Conditioning Assembly (Orbiter) - During APS operation, when amount of propellant vapor (P/T) within main engine tanks falls below 0.0566 $lbf/in^2a/°R$, additional propellant is resupplied from liquid storage tanks. This propellant is first circulated through a passive heat exchanger, where it is vaporized and superheated to desired resupply temperatures. The propellant conditioning assembly is composed of main engine tanks, multiple tube/heat exchanger, and associated controls for propellant resupply. The passive heat exchanger design concept is shown in Figure 4-10. Hydrogen and oxygen heat exchangers are made of aluminum tubing to achieve high heat transfer rates and minimum weight. Figure 4-10 shows how the tubes are attached to tank longitudinal structural stiffeners. The section modulus of the tube and flange adds to longitudinal rib stiffness, permitting a reduction in tank rib height and weight. However, the weight reduction can only be applied to the oxygen tank since the hydrogen rib height is at the minimum required for riveting. Heat exchanger design characteristics, including dimensions, are tabulated in Figure 4-11. The oxygen heat exchanger is divided into two panels, 17.5 ft long, each with 154 tubes, approximately 0.4 inch in diameter. The hydrogen heat exchanger is divided into four 15 ft panels, each consisting of sixty-two 0.3 in. diameter tubes. Propellant gas velocities in the tubes are limited to Mach 0.3. Conditioning assemblies were sized (tube length, spacing, etc.) to maintain final tank pressures of approximately 20 lbf/in^2a. Heat exchanger design inlet pressures are 35 lbf/in^2a for oxygen and 57 to 35 lbf/in^2a for hydrogen. Resupply flow rates are established by a pressure/temperature controller which is



PASSIVE HEAT EXCHANGER CONCEPT

FIGURE 4-10

TYPE	MULTIPLE TUBE/HEAT SINK
LOCATION	INTEGRAL WITH MAIN ENGINE TANK WALL
ATTACHMENT	TUBE FLANGE RIVETED TO TANK LONGITUDINAL STIFFENERS
TUBE CHARACTERISTICS	
MATERIAL	2014-T6 ALUMINUM
DENSITY, LBM/IN^3	0.101
DESIGN TEMPERATURE, ^oR	530
ULTIMATE STRESS, LBF/IN^2	64,000
ULTIMATE SAFETY FACTOR	2.0
MINIMUM GAGE, INCHES	0.022
MAXIMUM MACH NUMBER	0.3

PANEL DIMENSIONS	OXYGEN	HYDROGEN
NUMBER OF PANELS	2	4
NUMBER OF TUBES	154	62
TUBE LENGTH, FT	17.5	15.0
TUBE SPACING, IN	4.0	10.0
TUBE DIAMETER, IN	0.394	0.298

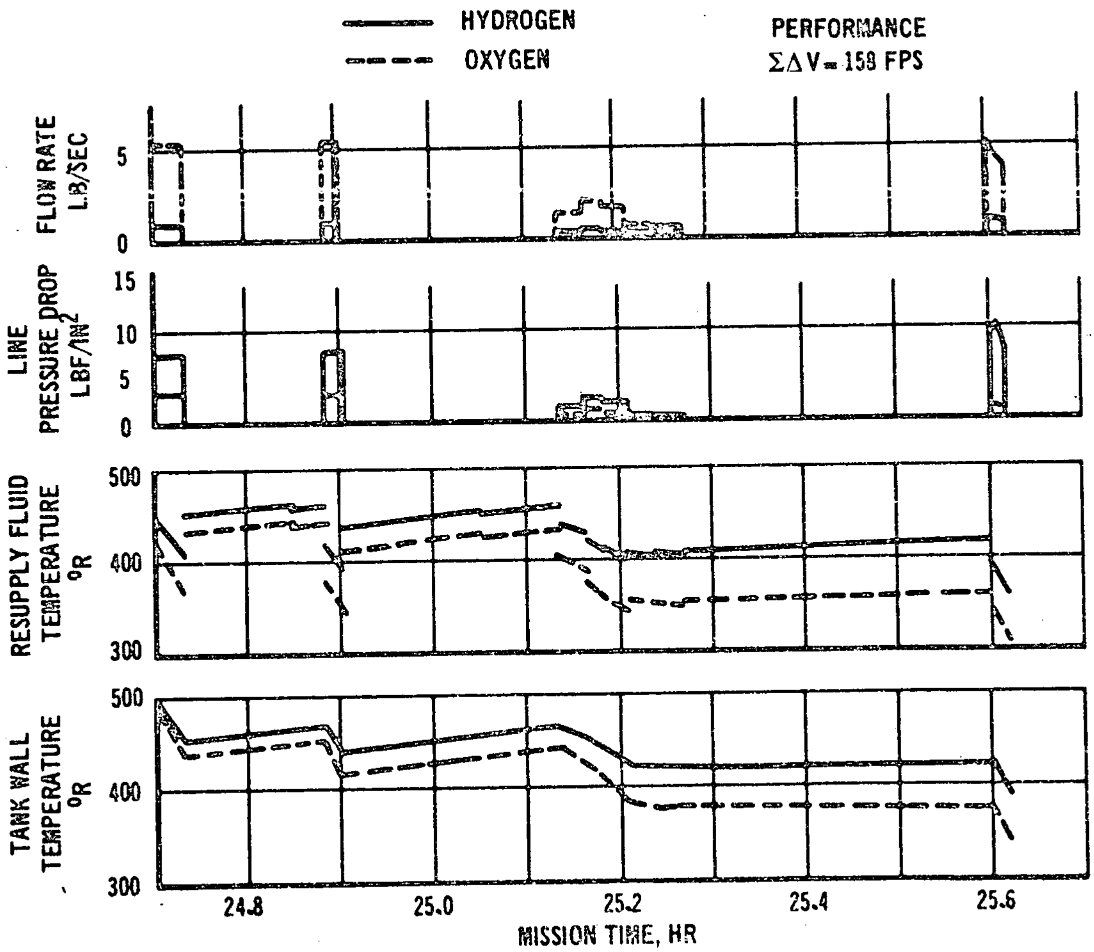
HEAT EXCHANGER DESIGN CHARACTERISTICS

FIGURE 4-11

designed to maintain a constant vapor mass within main engine tanks at all times. Flow modulation is achieved with valve-orifice subassemblies.

Figure 4-12 illustrates propellant conditioning assembly performance for the seventeenth orbit rendezvous mission. Time histories are presented for heat exchanger flow rates and pressure drops, propellant resupply temperatures, and tank wall temperatures. As shown at the completion of critical events such as braking and docking, propellant resupply temperatures are still quite high and line pressure drops are acceptable.

Main Engine Tanks-Liquid/Vapor Separators (Orbiter) - Liquid residuals are not required for satisfactory APS operation, but do offer a reduction in APS propellant requirements. However, large liquid quantities cannot be ingested into the APS distribution network. Therefore, if residuals are to be used a means of main engine tank liquid-vapor separation must be implemented. Liquid hydrogen residuals



HEAT EXCHANGER OPERATION (SEVENTEENTH ORBIT RENDEZVOUS)

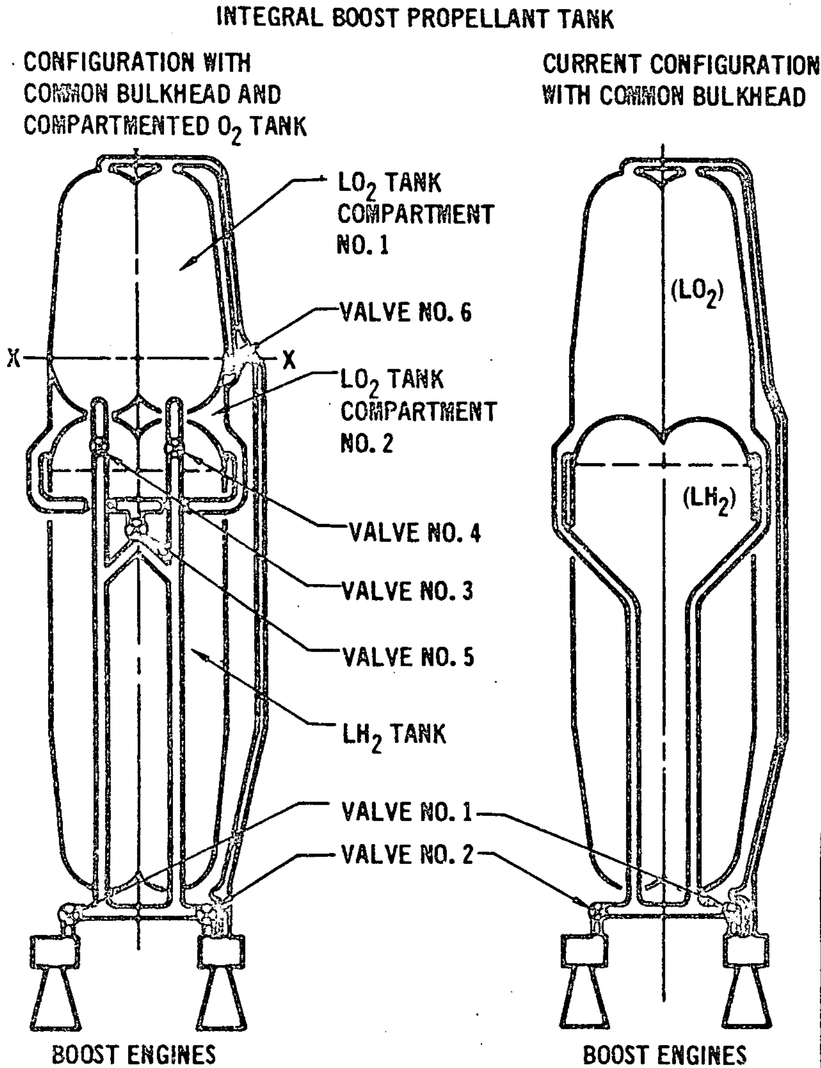
Braking and Docking Maneuvers

FIGURE 4-12

are of little benefit to the APS due to rapid boiloff and, therefore, they are dumped through the main propulsion subsystems immediately after orbit insertion. Liquid oxygen, on the other hand, is retained in a compartmented tank (as shown in Figure 4-13). A tension bulkhead is installed above the common liquid oxygen/liquid hydrogen compression bulkhead to absorb liquid head loads acting on the latter structure during high launch g. The volume between the two bulkheads is loaded with liquid oxygen; thus, there is no loss in oxygen tank volume. Inasmuch as the compression bulkhead is thus isolated from the high launch head pressures, its weight is significantly reduced and the two bulkheads weigh no more than the one compression bulkhead in the original tank design. Total weight penalty incurred is 50 lb.

Operating sequence for the compartmented oxygen tank is: 1) during prelaunch, both compartments are filled with liquid oxygen, 2) during main engine operation, the primary liquid oxygen tank drains first leaving it dry and ready for use as a gaseous accumulator with liquid residuals trapped in the suction lines and smaller tank compartment at main engine shutdown, and 3) during orbital operation, the flow of propellant vapors from the smaller-to-larger tank compartments replenishes propellant mass extracted during APS usage. Propellant communication between the two tank compartments persists as long as liquid residual quantity and main tank heat leaks result in a boiloff rate and associated pressure rise sufficient for mass transfer. Valve sequencing for this operation is shown in Figure 4-13.

<u>Liquid/Vapor Mixer Assembly (Orbiter)</u> - During low demand attitude control operations, all propellant is extracted from the main engine tanks; there is no downstream liquid injection in the liquid/vapor mixer. For major APS operations, the mixer assembly provides constant pressure and temperature at the engine inlets, thus achieving constant thrust level and mixture ratio. The mixer assembly consists of a liquid injection/vapor mixing chamber and two independent controls - a pressure regulator located downstream of the mixing chamber, and a liquid flow rate controller. Cold liquid propellant is injected into the mixing chamber, where it is combined with warm propellant vapors (extracted from the tank) to achieve a constant propellant density corresponding to predefined mixer temperature and regulated pressure. Minimum engine inlet temperatures are 200°R for oxygen and 150°R for hydrogen, based on engine ignition criteria and maximum allowable injector temperature differential. Mixer physical characteristics required to achieve these conditions are shown in Figure 4-14.



SEQUENCE OF OPERATION FOR CONFIGURATION WITH COMPARTMENTED O_2 TANK

EVENT	VALVE OPERATION	REMARKS
PRELAUNCH	NOS. 1 & 2 CLOSED NOS. 3, 4, 5, 6 OPEN	LOAD COMPARTMENTS NOS. 1 & 2
LIFTOFF	ALL VALVES OPEN EXCEPT NO. 5	ALL LO_2 FLOW FROM COMPARTMENT NO. 1
LO_2 SUPPLY DEPLETED TO LEVEL X–X	OPEN NO. 5	LO_2 FLOW FROM COMPARTMENTS NO. 1 & 2
END OF BOOST	CLOSE ALL VALVES EXCEPT NO. 5	ALL O_2 RESIDUALS ARE CONTAINED IN COMPARTMENT NO. 2.

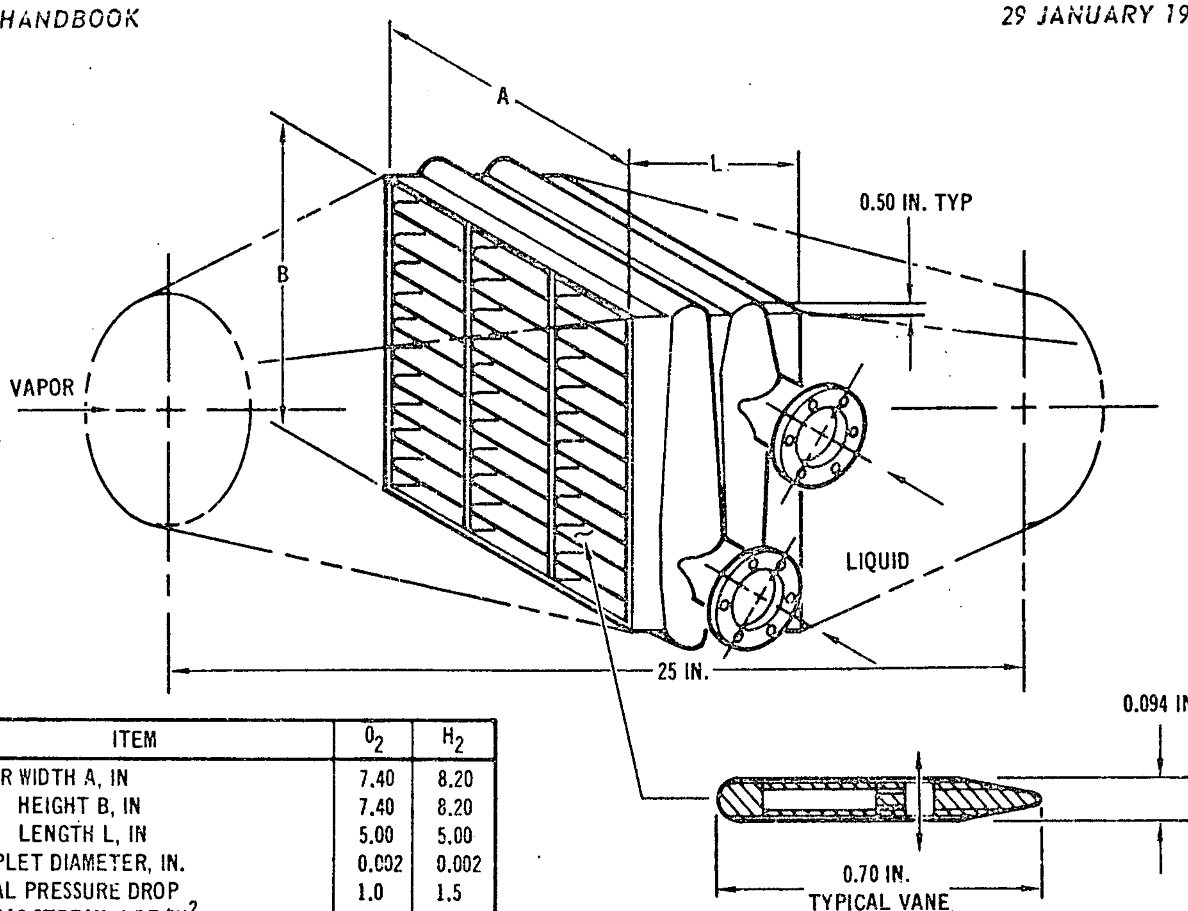
ORBITER TANK WEIGHT COMPARISON

ITEM	BOOST TANK CONFIGURATION: COMMON BULKHEAD	BOOST TANK CONFIGURATION: COMPARTMENTED O_2 TANK
COMMON BULKHEAD	950 LB	540 LB
COMPARTMENT BULKHEAD	–	210 LB
VALVES	–	175 LB
LINES AND MOTION COMPENSATORS	–	75 LB
	950 LB	1000 LB

FIGURE 4-13

COMPARTMENTED OXYGEN PROPELLANT TANK

ORBITER



ITEM	O_2	H_2
MIXER WIDTH A, IN	7.40	8.20
HEIGHT B, IN	7.40	8.20
LENGTH L, IN	5.00	5.00
DROPLET DIAMETER, IN.	0.002	0.002
TOTAL PRESSURE DROP GAS STREAM, LBF/IN^2	1.0	1.5
PRESSURE DROP, LIQUID, LBF/IN^2	10.0	7.8
GAS STREAM MACH NO.	0.2	0.2
LIQUID DISCHARGE VELOCITY,MAX,FPS	20	47

PROPELLANT LIQUID/VAPOR MIXER FIGURE 4-14

Liquid/vapor mixer design is similar for both oxygen and hydrogen propellants, consisting of a liquid injection element, with hyperthin vanes located normal to the gas stream, and a downstream mixing length to allow liquid vaporization. Liquid flow is controlled by a motor driven cavitating venturi throttle valve to provide a prescribed temperature at the mixing chamber outlet. This valve maintains constant liquid injection pressure and decouples liquid flowrate from mixing chamber pressure fluctuations. The pressure regulator is a motor driven IRIS or petal-type throttle valve (shown in Figure 4-15). A pressure transducer is located downstream of the IRIS valve and valve flow area is controlled electrically to provide a predefined pressure.

Performance characteristics for the liquid/vapor mixer assembly are shown in Figures 4-16 and 4-17. In Figure 4-16, the oxidizer mixer inlet and outlet temperatures, pressures, and flow rates are shown as a function of burn time. Initially, when the temperature of the gas being removed from the main engine tank is high, a large quantity of liquid can be used. As tank temperature and pressure decay with

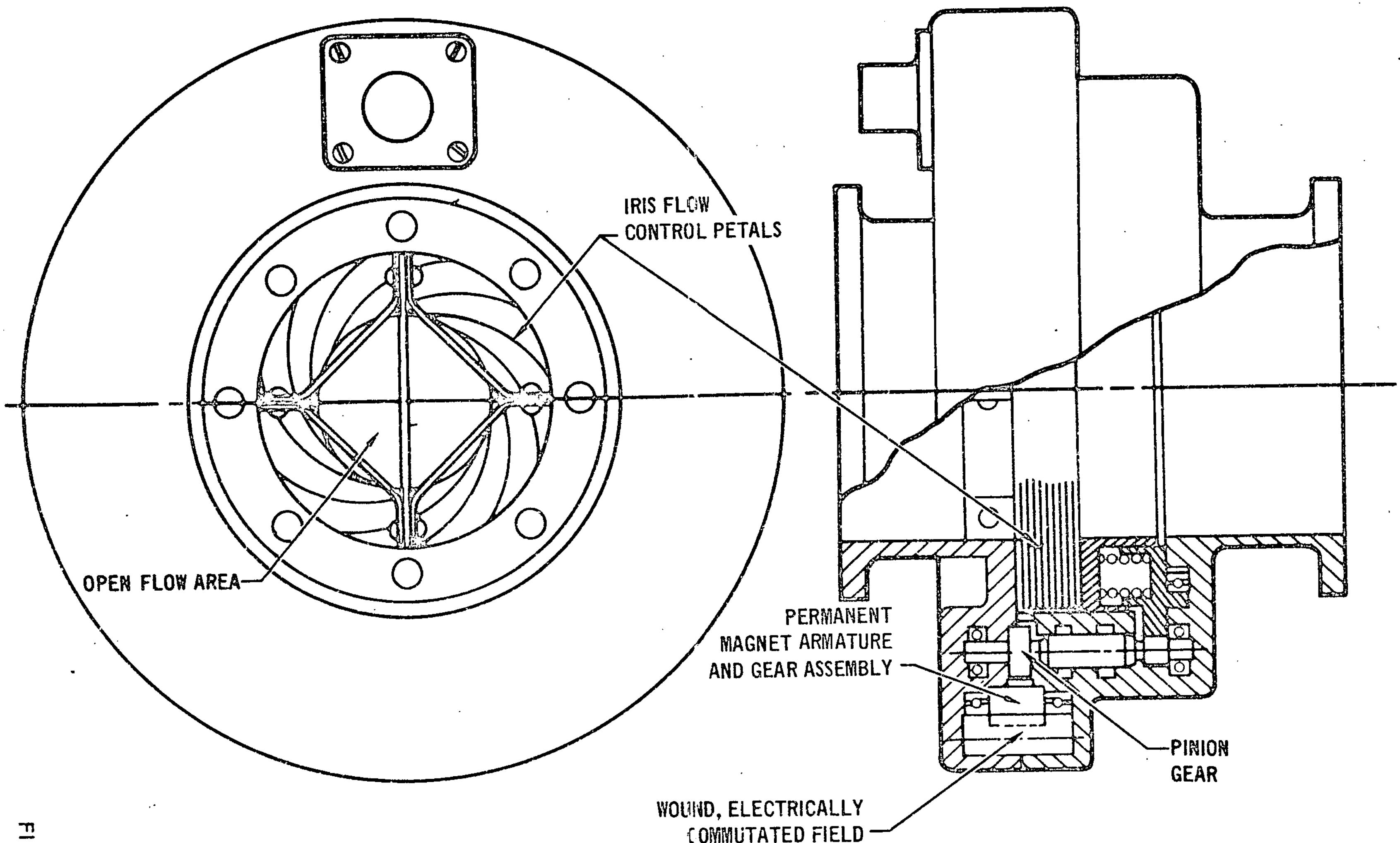
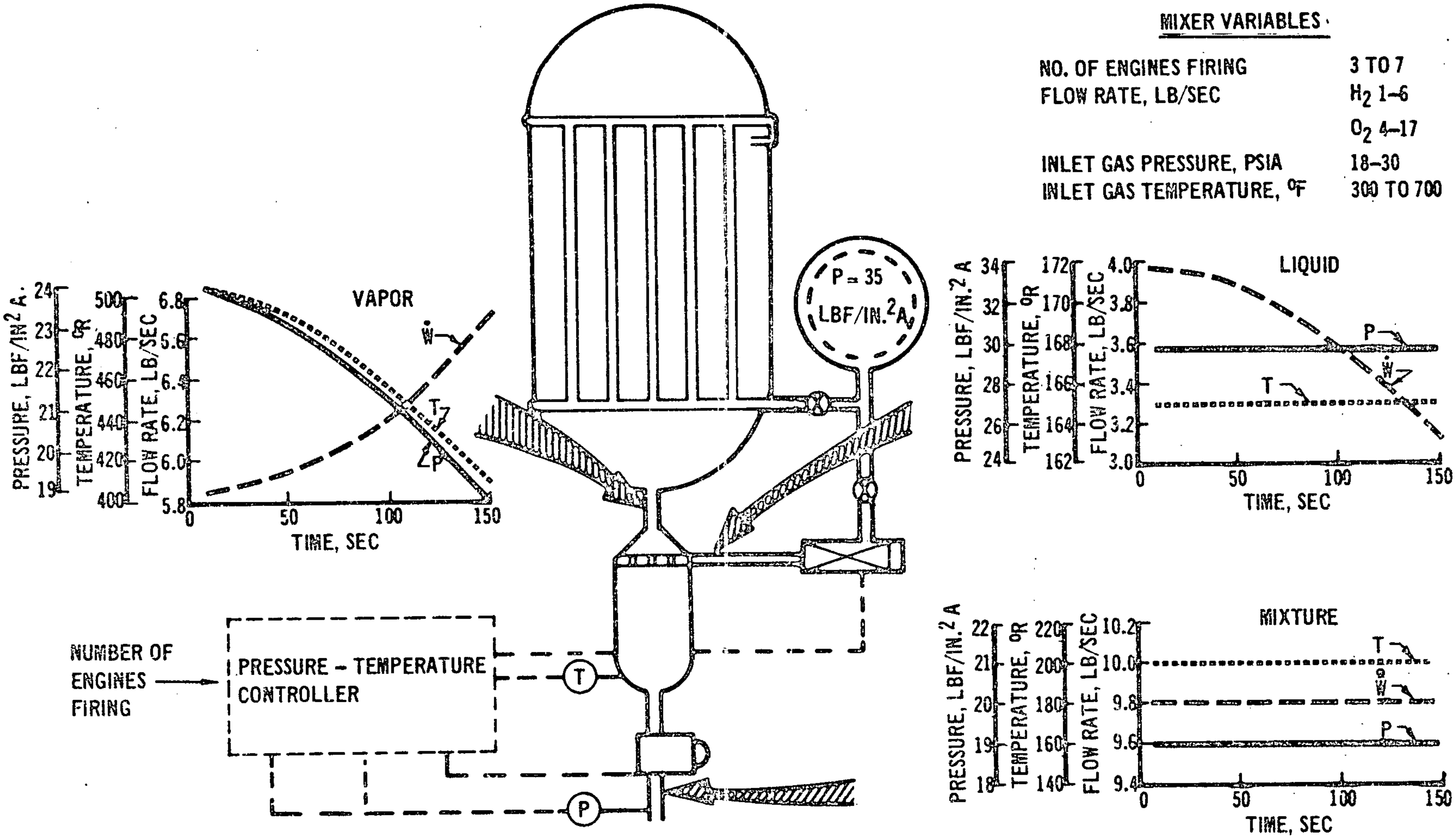


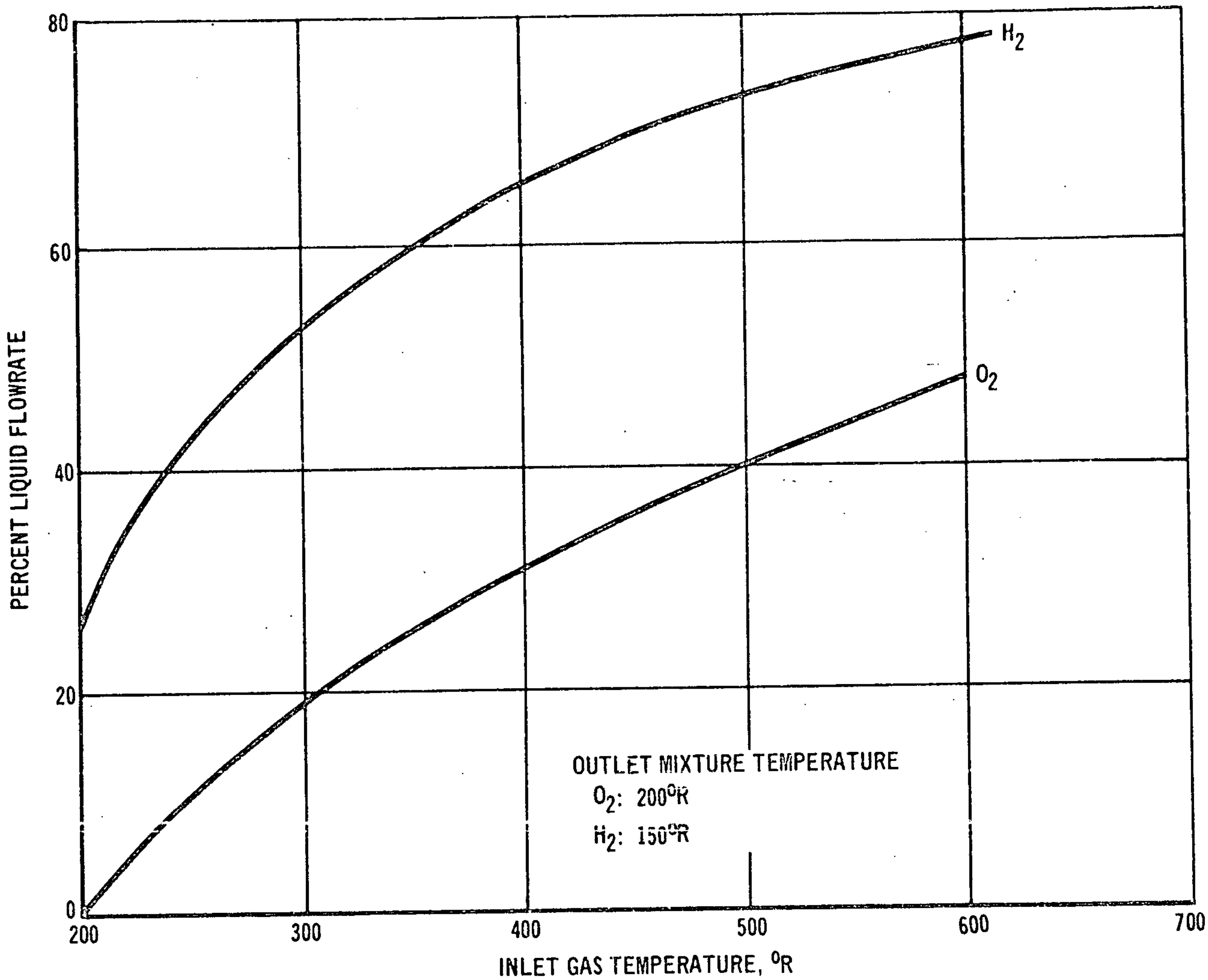
FIGURE 4-15

IRIS REGULATOR DESIGN



LIQUID - VAPOR MIXER

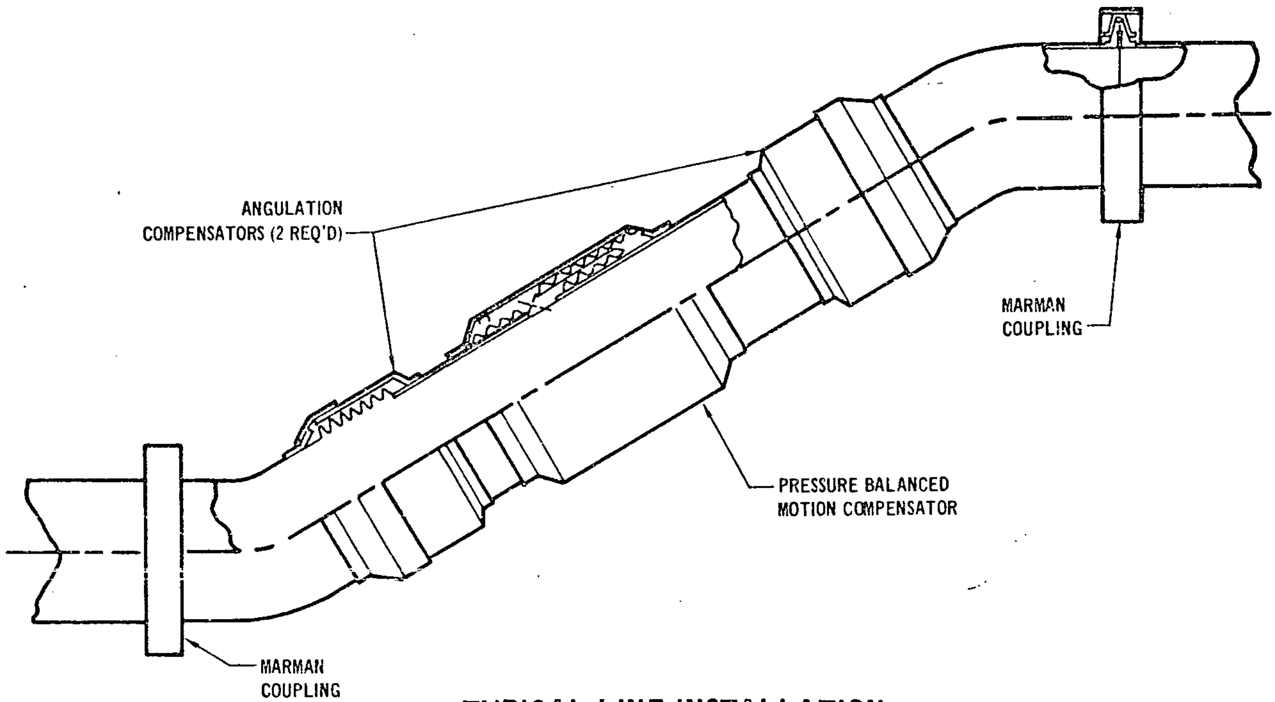
Steady State Operating Characteristics – Oxygen



LIQUID/VAPOR MIXER
LIQUID FLOW RATE TO PROVIDE REQUIRED OUTLET TEMPERATURES FIGURE 4-17

time, liquid flow rate must be decreased to maintain desired mixer outlet conditions. More propellant must then be extracted from the main engine tank to support steady state conditions at the mixer outlet. Figure 4-17 gives the liquid flow rates required to maintain desired outlet temperatures. Weight estimates for the mixer are 11.4 lb (H_2) and 17.4 lb (O_2) with an additional 22.0 lb required on each propellant side for throttle valves.

Propellant Distribution Assembly (Orbiter) - The propellant distribution assembly supplies propellant from the liquid/vapor mixer assembly to the engine assemblies and provides engine isolation in case of failure. Ducts, valves, and linear and angular compensators make up this assembly. The distribution assembly installation is shown in Figure 4-1. Each section of ducting includes linear and angular compensators as required to absorb normal manufacturing tolerances in the vehicle, to absorb the differences in thermal expansion between ducts and vehicle structure, and to compensate for structural motion. A typical line and compensator installation is shown in Figure 4-18. Bulk liquid propellants are prevented from entering the distribution network and adversely affecting engine performance by dumping liquid hydrogen and by trapping liquid oxygen in the compartmented main engine tank.



TYPICAL LINE INSTALLATION

FIGURE 4-18

Line routing and valving are typified by the oxygen distribution assembly shown in schematic Figure 4-19. Isolation valves are located (as shown) to provide shutdown of engine groups when necessary. To minimize weight, main engine tank pressurization lines are used as primary APS distribution trunklines. These lines extend nearly the full length of the orbiter and are of sufficient diameter (8.2 in.) to accommodate APS flow requirements. All remaining lines were sized to provide minimum subsystem weight by balancing line weight penalty (a function of friction losses) and engine weight penalty (a function of resultant chamber pressures) for the maximum number of engines that could be fired simultaneously. Line diameters and lengths are given in Figure 4-19. Maximum span between line supports is shown in Figure 4-20 for the line diameters of interest. Network design characteristics are given in Figure 4-21. All lines are fabricated from minimum gage 2219 aluminum and contain linear and angular, bellows-type compensators, also constructed of 2219 aluminum. Component weights (lb) for oxidizer and fuel dis-

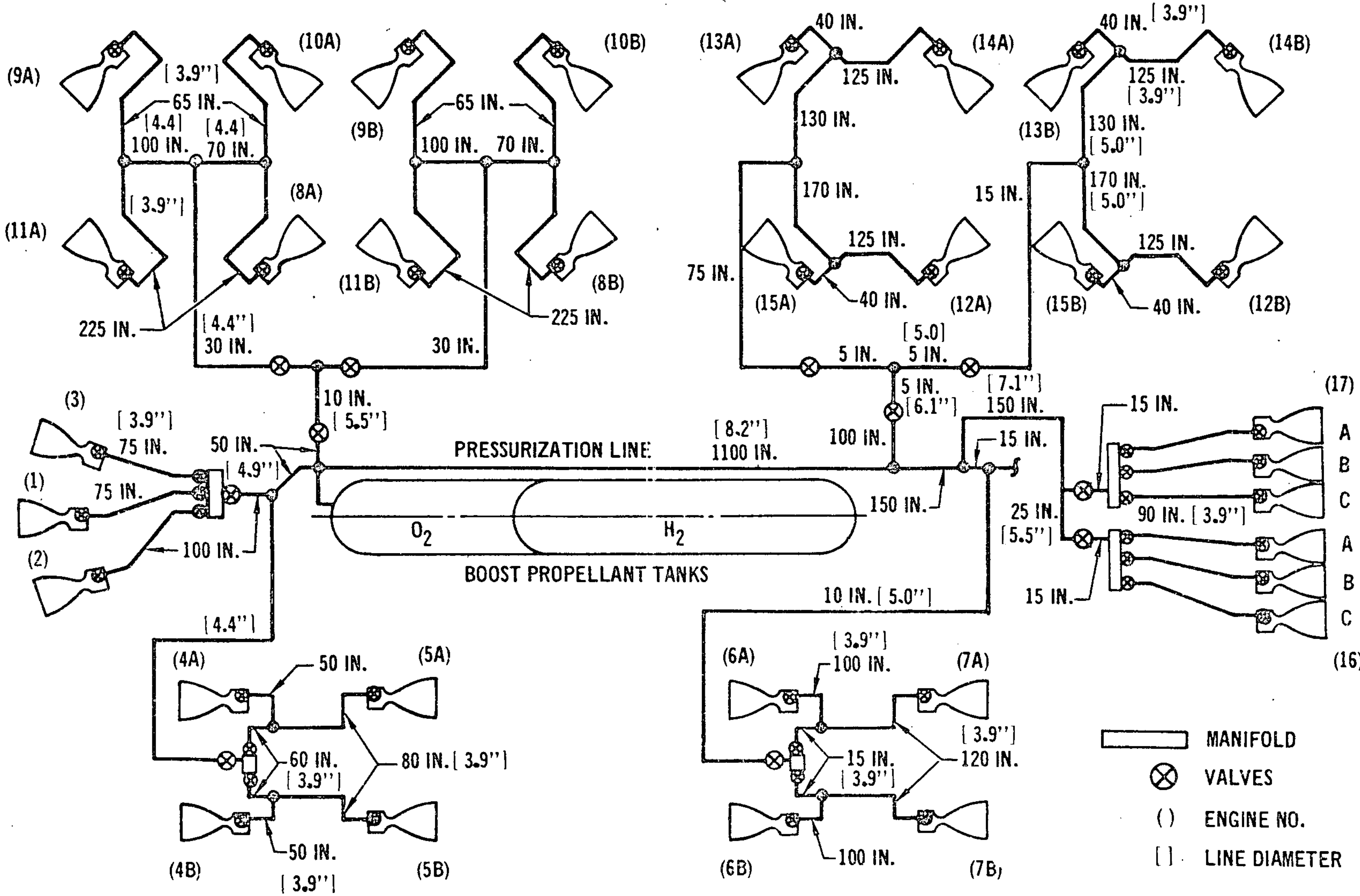
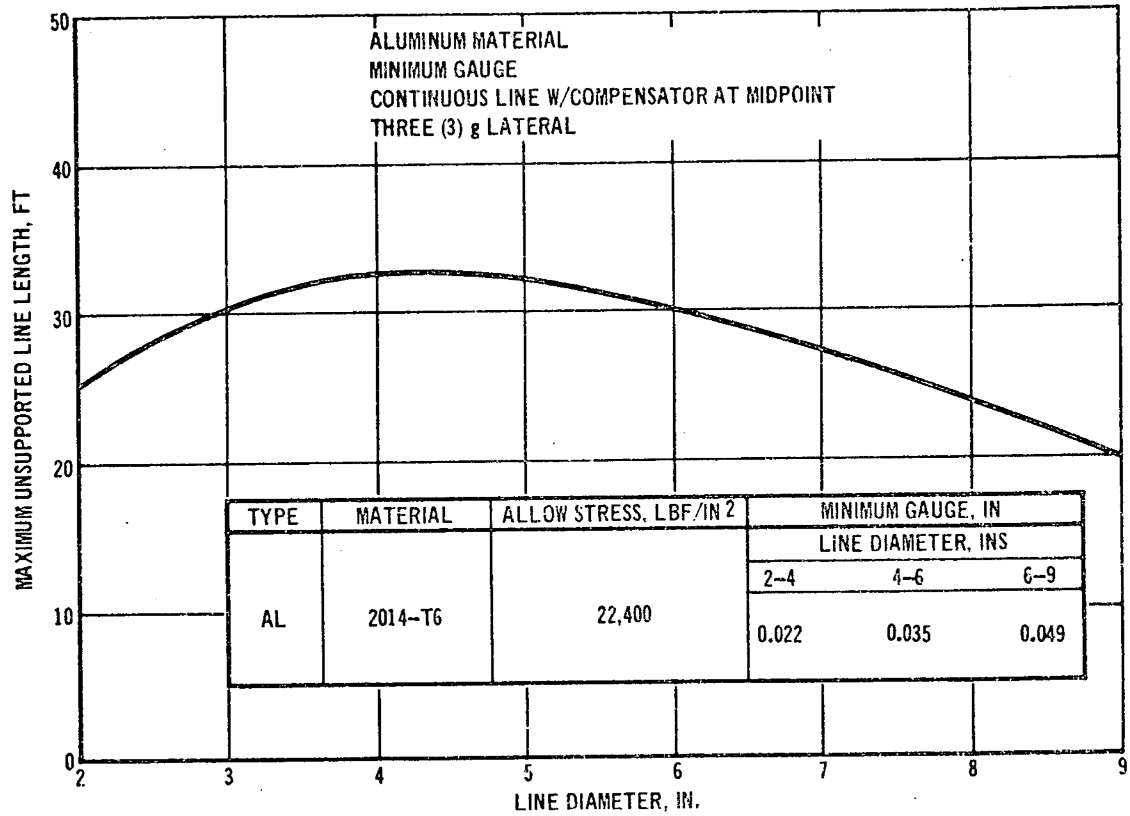


FIGURE 4-19

DISTRIBUTION NETWORK

ORBITER DISTRIBUTION (OXYGEN SIDE)



TYPE	MATERIAL	ALLOW STRESS, LBF/IN ^{2}	MINIMUM GAUGE, IN LINE DIAMETER, INS		
			2–4	4–6	6–9
AL	2014–T6	22,400	0.022	0.035	0.049

MAXIMUM SPAN BETWEEN LINE SUPPORTS

FIGURE 4–20

DISTRIBUTION LINES	
MATERIAL	2219 ALUMINUM
DENSITY (LB/IN.^{3})	0.101
DESIGN TEMPERATURE (^{0}R)	530
ULTIMATE STRESS LBF/IN.^{2}	64,000
ULTIMATE SAFETY FACTOR	2.0
MINIMUM GAGE (INS)	
LINE DIAMETER 2–4	0.022
4–6	0.035
6–9	0.049
COMPENSATORS	
TYPE, ANGULAR	SOCKET/BELLOWS
LINEAR	IN LINE BELLOWS
MATERIAL	2219 ALUMINUM
ISOLATION VALVES	
TYPE	VISOR
MATERIAL	ALUMINUM
ACTUATION	DC REVERSIBLE MOTOR DRIVE WITH CLUTCH BRAKE

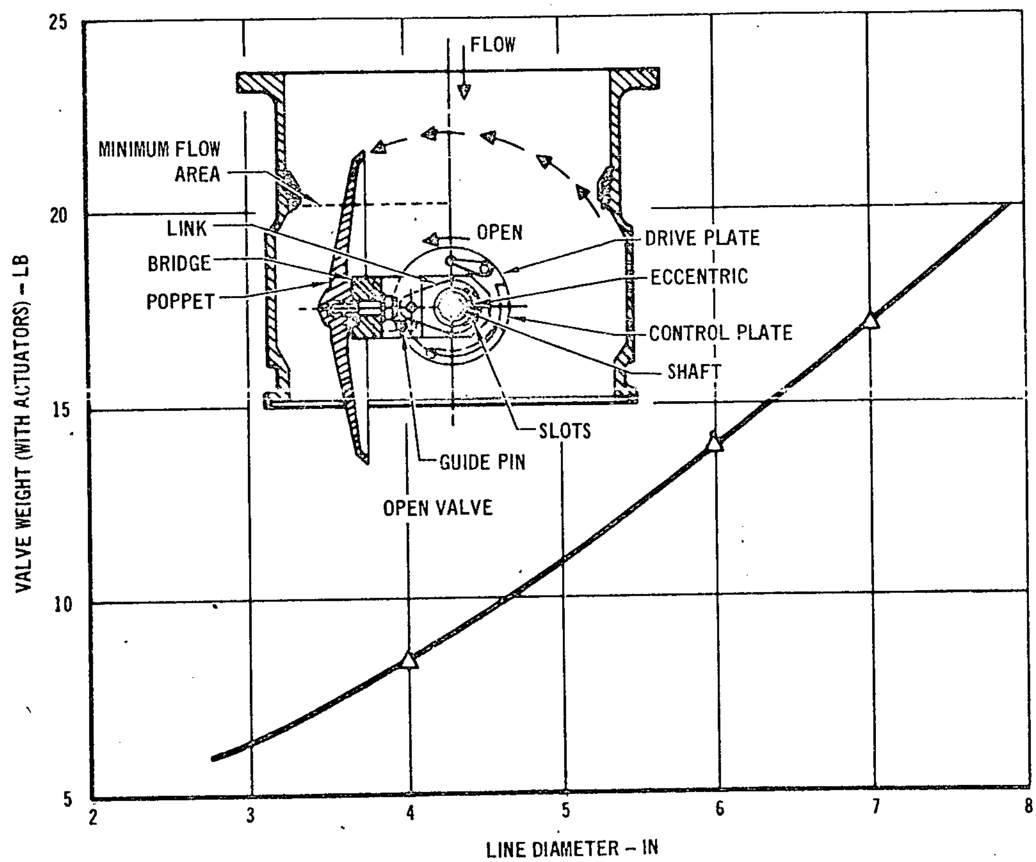
DISTRIBUTION ASSEMBLY DESIGN CHARACTERISTICS
(Oxygen and Hydrogen)

FIGURE 4–21

tribution networks are:

Lines	432
Linear Compensators	224
Angular Compensators	144
TOTAL	800

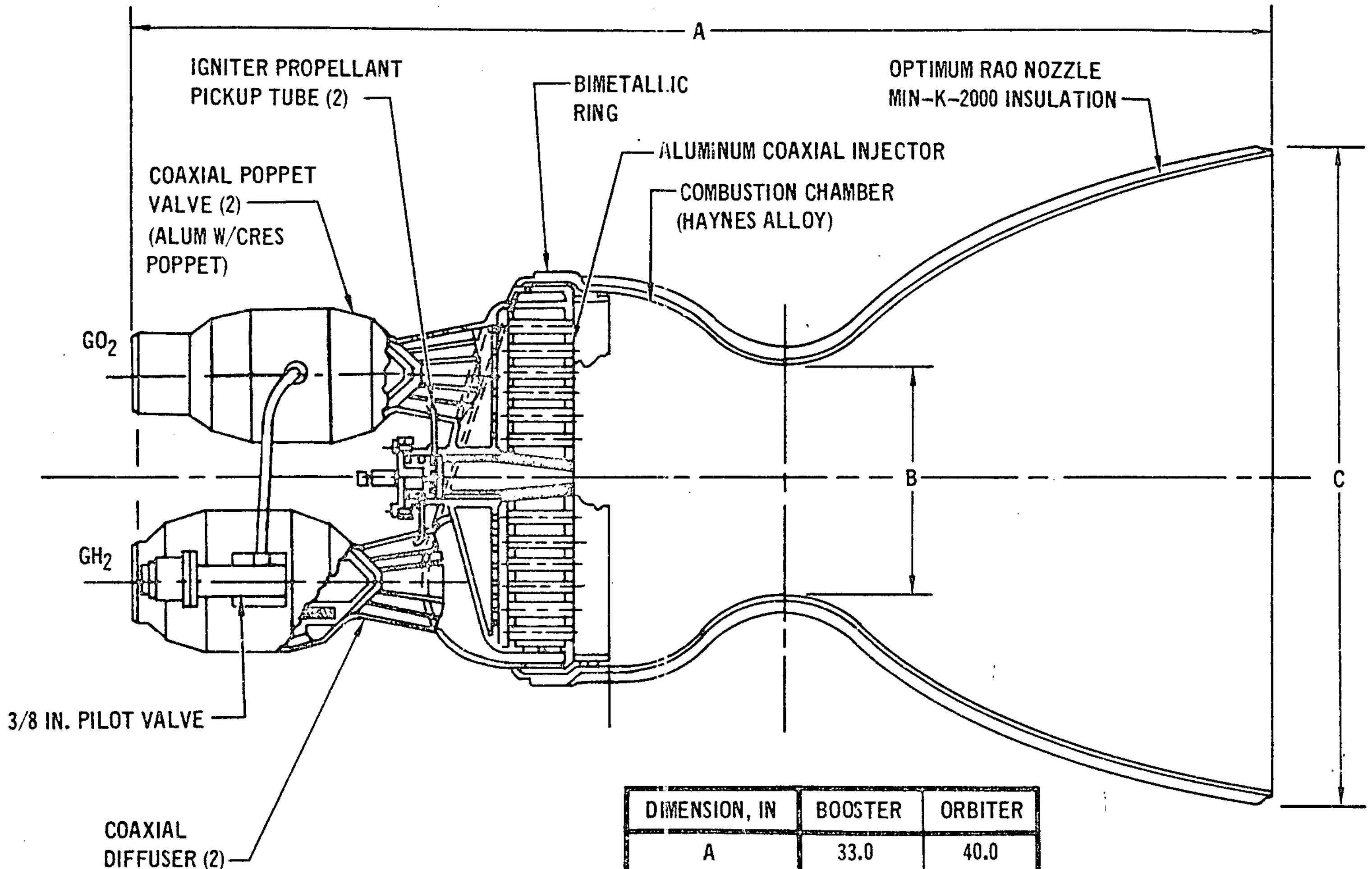
Visor-type isolation valves are used to minimize envelope, weight, and pressure losses. Valve actuation is achieved with a dc reversible motor drive with clutch brake. Valve weights, including actuators, are given in Figure 4-22 for the diameters of interest. Total isolation valve weight is 472 lb.



ISOLATION VALVE DESIGN AND WEIGHT
(Visor-Type)

FIGURE 4-22

Engine Assemblies (Orbiter) - APS engine assemblies provide all attitude control, Y and Z axes translation maneuvers, and X axis vernier translation maneuvers for the space shuttle orbiter. Thirty-three 1080 lb thrust engines are used in the subsystem. An engine assembly includes propellant control valves, injector, combustion chamber, and nozzle. Orbiter engine design and dimensions are given in Figure 4-23. The engine assembly is a hydrogen film-cooled design containing a mul-



DIMENSION, IN	BOOSTER	ORBITER
A	33.0	40.0
B	14.2	8.0
C	21.0	24.0

ENGINE ASSEMBLY

FIGURE 4-23

tiple element, coaxial injector and an 8:1 optimum Rao contour nozzle for improved performance. Combustion chamber and nozzle are fabricated of thin wall, high temperature steels, while the engine head end assembly is constructed of aluminum to minimize weight. The dissimilar materials are attached by means of a hydrogen-cooled bimetal joint. Ignition is achieved by means of an electric spark torch igniter, while pneumatically actuated, pilot operated, coaxial valves provide a 50 ms opening response at a pilot valve inlet pressure of 250 lbf/in^{2}a. A single solenoid pilot valve on each engine provides simultaneous actuation of both propellant valves. Valve design is illustrated in Figure 4-24. A conical diffuser at the valve exit limits pressure drop to 1.0 lbf/in^{2}a at design flow rates. Figure 4-25 presents valve design criteria, and Figure 4-26, the valve pneumatic actuation requirements. Gaseous helium requirements are 2.6 x 10^{-4} lb per valve cycle. The pneumatic subassembly schematic is shown in Figure 4-27. The helium is stored at 3500 lbf/in^{2}a in three titanium tanks. Total helium requirements are 11 lb and total pneumatic subassembly weight is 193 lbs.

The engine delivers 1080 lb thrust at a vacuum specific impulse of 376 sec under the following design and operating conditions:

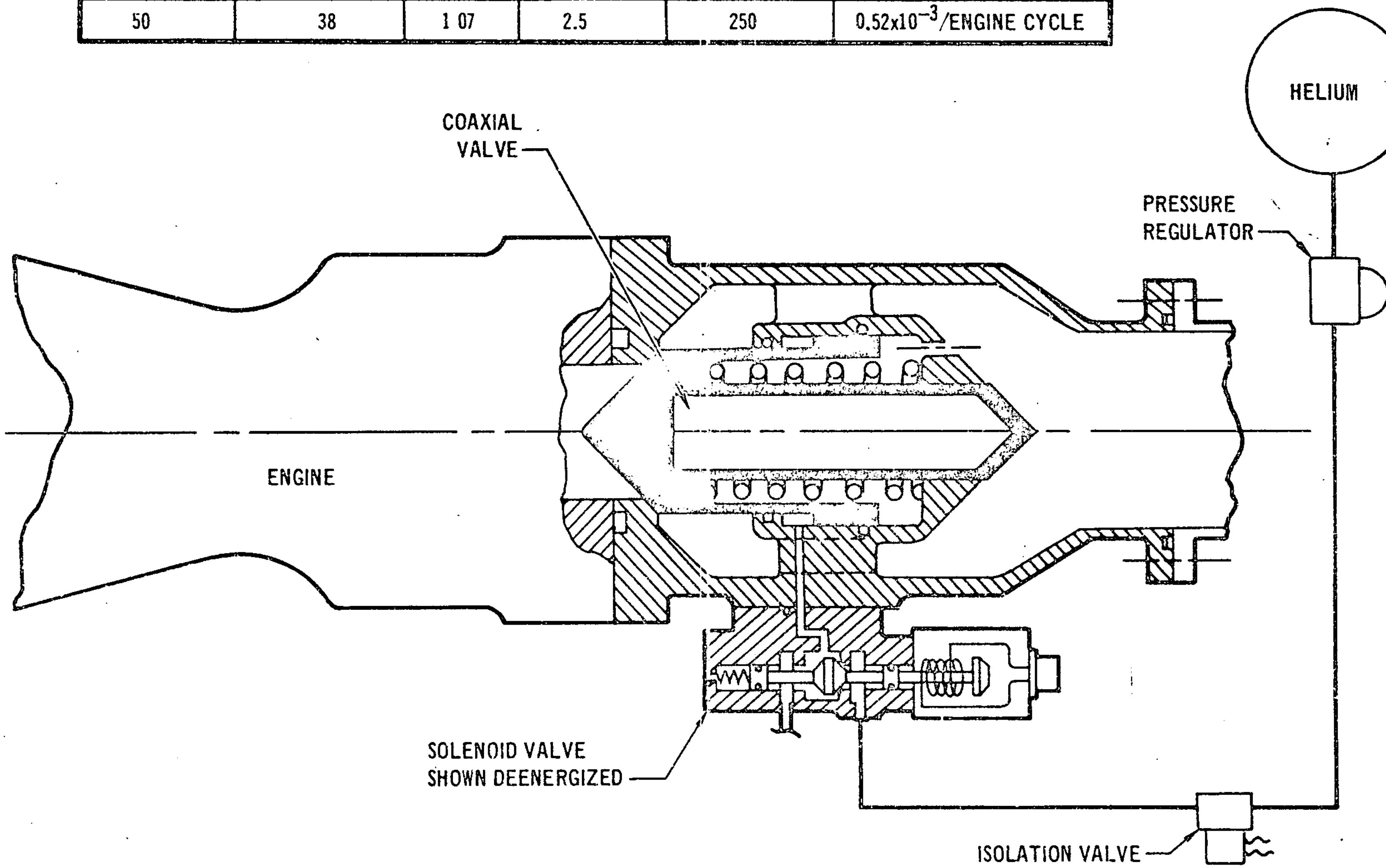
inlet pressure, lbf/in^{2}a	15.7
inlet temperature, °R	200 (O_2)
	150 (H_2)
chamber pressure, lbf/in^{2}a	13.7
mixture ratio, O/F	3.0

Engine performance (i.e., mixture ratio, chamber pressure, vacuum thrust, and vacuum specific impulse) sensitivity to inlet temperature variations are shown in Figures 4-28 and 4-29, while sensitivity to inlet pressure variations are given in Figures 4-30 and 4-31.

Start and shutdown of the pitch-roll engines are shown in Figure 4-32 for inlet temperatures of 380° and 445°R for oxidizer and fuel, respectively. These are representative values for low-demand attitude control operation, since all propellant is supplied from the main engine tanks. Opening and closing of fuel and oxidizer valves is, essentially, simultaneous. Valve response time, fuel and oxidizer injector pressures, and chamber pressure time histories are shown in Figure 4-32. Engine minimum impulse bit was 61 lb-sec at a vacuum specific impulse of 338 sec.

Engine design conditions, component weights, and dimensions are summarized in Figure 4-33. Engine weight is 77 lb per assembly.

VALVE DESIGN				ACTUATOR REQUIREMENTS	
RESPONSE (MSEC)	SEAT LOADS (LB/IN)	STROKE (IN)	CAVITY VOL (IN^3)	PRESSURE (LB/IN^2 A)	HELIUM (LB)
50	38	1 07	2.5	250	$0.52x10^{-3}$/ENGINE CYCLE



PNEUMATIC VALVE ACTUATOR SYSTEM

FIGURE 4-24

	FUEL	OXIDIZER
FLOWRATE, LB/SEC	0.702	2.106
PRESSURE DIFFERENTIAL, LBF/IN^2	1	1
TEMPERATURE, INLET, °R	150	200
EQUIVALENT FLOW DIAMETER, IN	2.54	2.35
CYCLE LIFE	650/MISSION	650/MISSION
ACTUATION TYPE	PNEUMATIC	PNEUMATIC
RESPONSE GOAL	0.030/0.050	0.030/0.050
WEIGHT – LB		
VALVES	7.3	6.4
PILOT VALVE	2.0	–

DESIGN CRITERIA FOR ORBITER ENGINE VALVES

FIGURE 4-25

PRESSURE REQUIRED, LBF/IN^2	250
VALVE SEALING ELEMENT SEAT LOAD, LB	328
ACTUATOR PISTON EFFECTIVE AREA, IN^2	2.36
CLOSING SPRING FORCE, LB	470
PISTON STROKE, IN	1.07
FRICTION FORCE, LB	121
GASEOUS HELIUM REQUIRED PER VALVE CYCLE, LB	0.026×10^{-2}
PILOT VALVE EQUIVALENT FLOW DIA., IN	0.250

PNEUMATIC ACTUATION REQUIREMENTS FOR ORBITER
Engine Coaxial Poppet Valve

FIGURE 4-26

4.2 Equipment Design and Operation (Booster) - The booster low pressure auxiliary propulsion subsystem contains two primary assemblies. These are:

1) a propellant distribution assembly and associated valves and controls
2) control engine assemblies.

The booster APS operates entirely from main engine tank liquid and vapor residual propellants, and no additional APS propellant tankage, turbopumps, conditioning equipment, or mixing assemblies are required. The following paragraphs describe these assemblies. Line routing and booster engine locations are shown in Figure 4-34 and the booster APS design summary is presented in Figure 4-35.

Main Engine Pressurant Heat Exchanger (Booster) - The initial hydrogen tank vapor temperature was reduced from 450°R (as specified by Reference (a)) to 260°R to increase main tank propellant density at main engine shutdown. This constraint was discussed in Section 3.2. Temperature reduction is accomplished by using a passive heat exchanger located on the main engine hydrogen feed line. In this manner, sufficient hydrogen residuals for full APS usage are accommodated without affecting booster and orbiter main engine commonality. The heat exchanger design

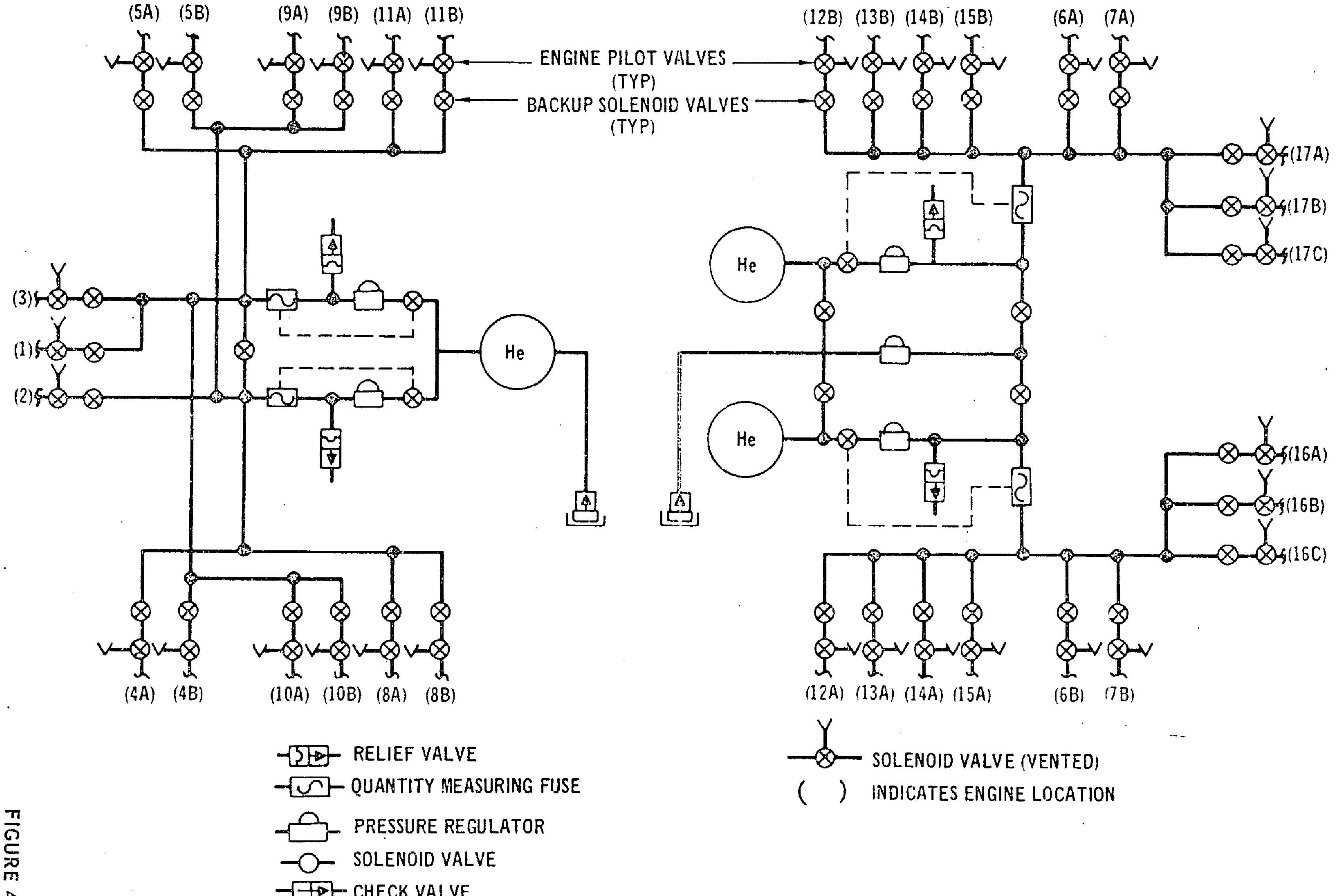
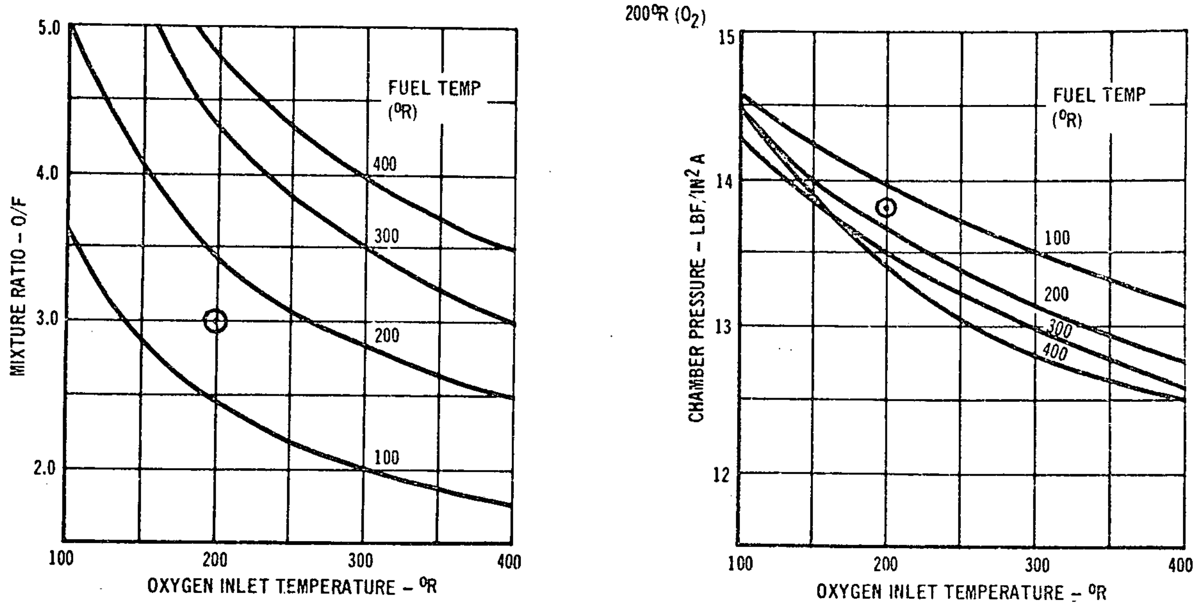


FIGURE 4-27

PNEUMATIC SUBASSEMBLY – ENGINE VALVE ACTUATION (ORBITER)

DESIGN POINT

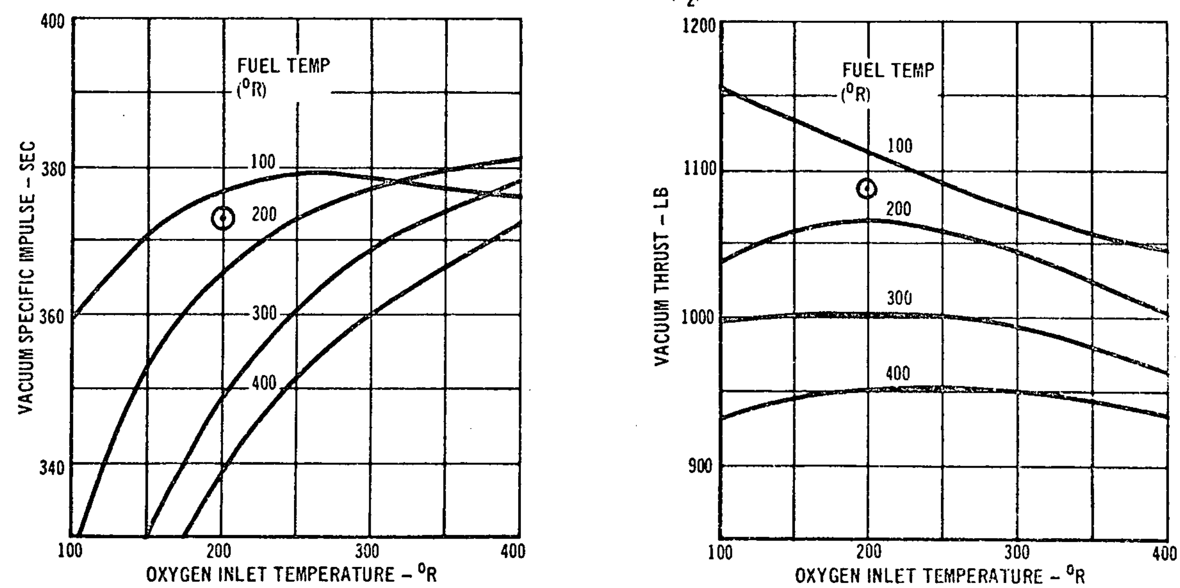
F = 1080 LB
PC = 13.7 LBF/IN^{2}A
MR = 3:1
ϵ = 8:1
T INLET = 150°R (H_2)
200°R (O_2)



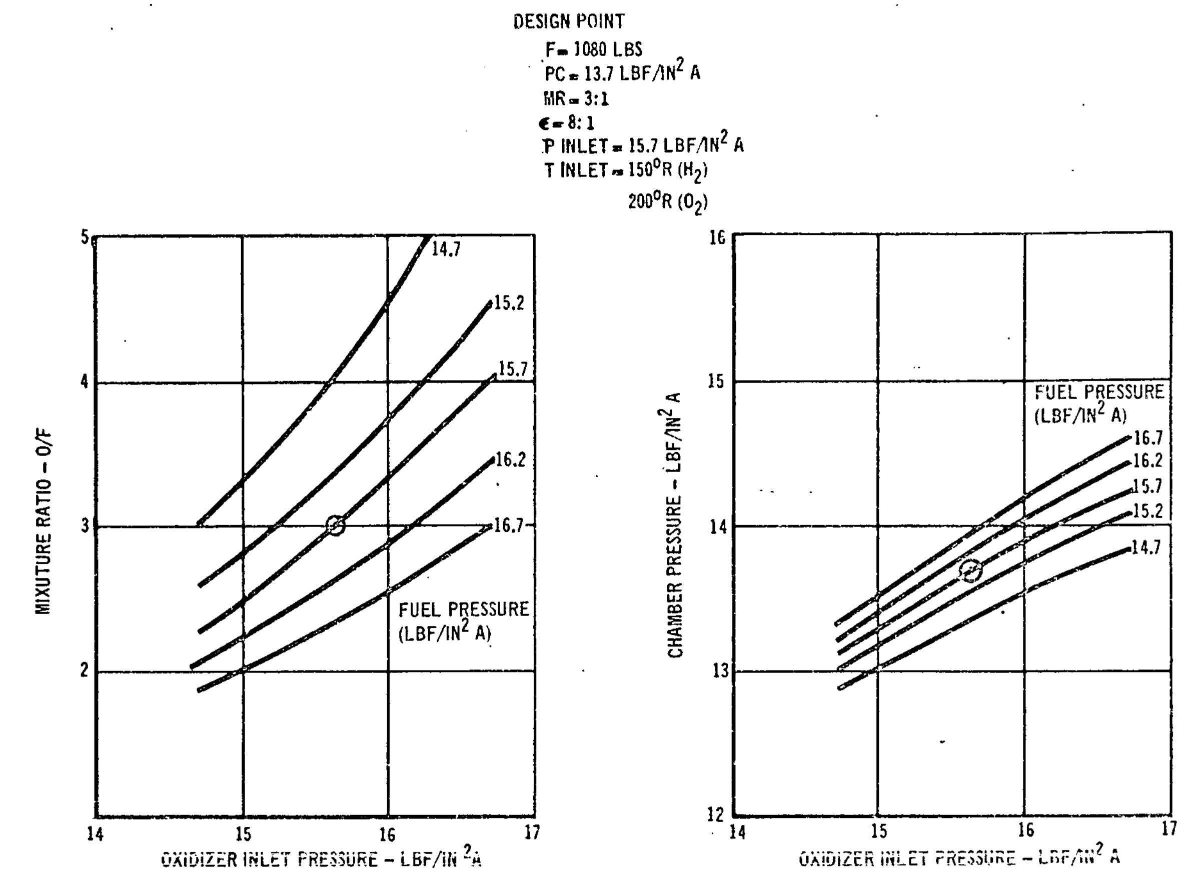
ENGINE PERFORMANCE SENSITIVITY TO INLET TEMPERATURE FIGURE 4-28

DESIGN POINT

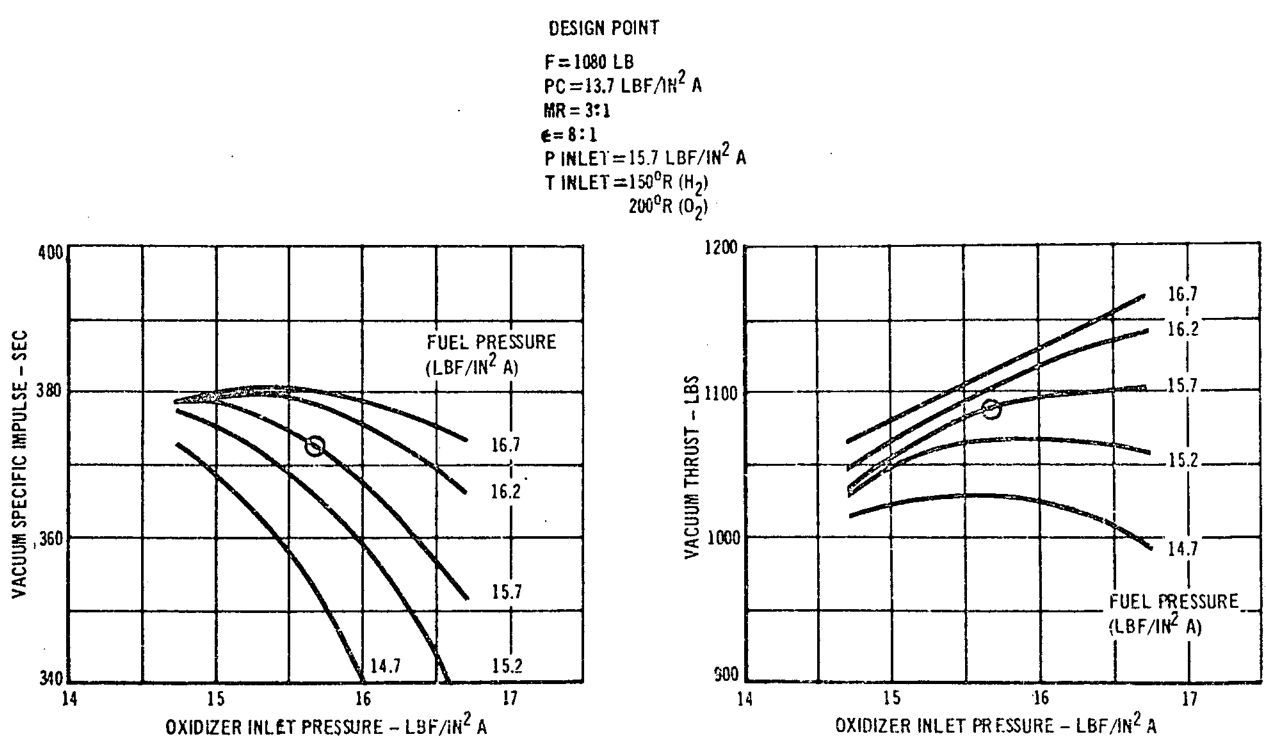
F = 1080 LB
PC = 13.7 LBF/IN^2 A
MR = 3:1
ϵ = 8:1
T INLET = 150°R (H_2)
200°R (O_2)



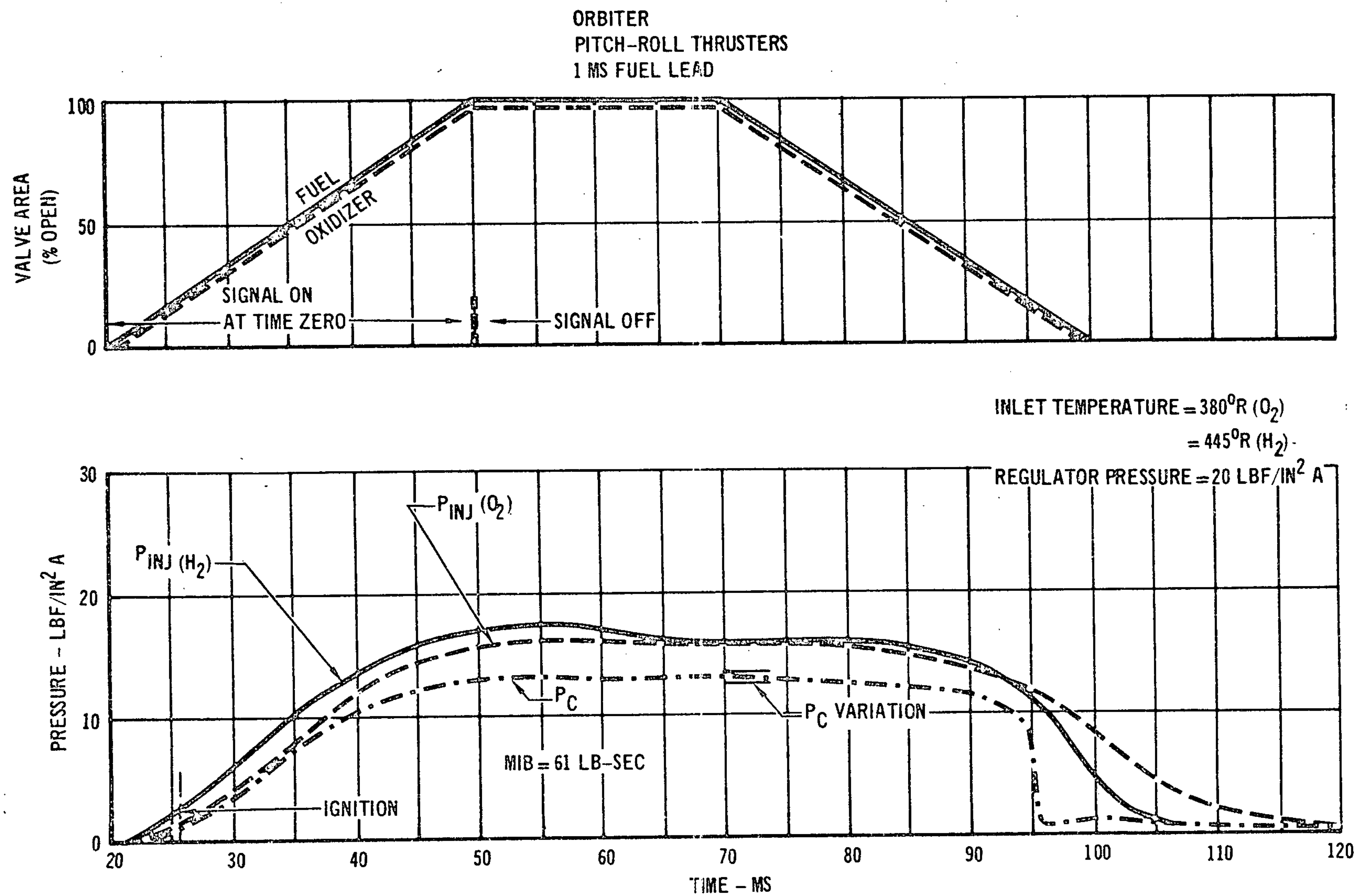
ENGINE PERFORMANCE SENSITIVITY TO INLET TEMPERATURE FIGURE 4-29



ENGINE PERFORMANCE SENSITIVITY TO INLET PRESSURE FIGURE 4–30



ENGINE PERFORMANCE SENSITIVITY TO INLET PRESSURE FIGURE 4–31



ENGINE RESPONSE CHARACTERISTICS

FIGURE 4-32

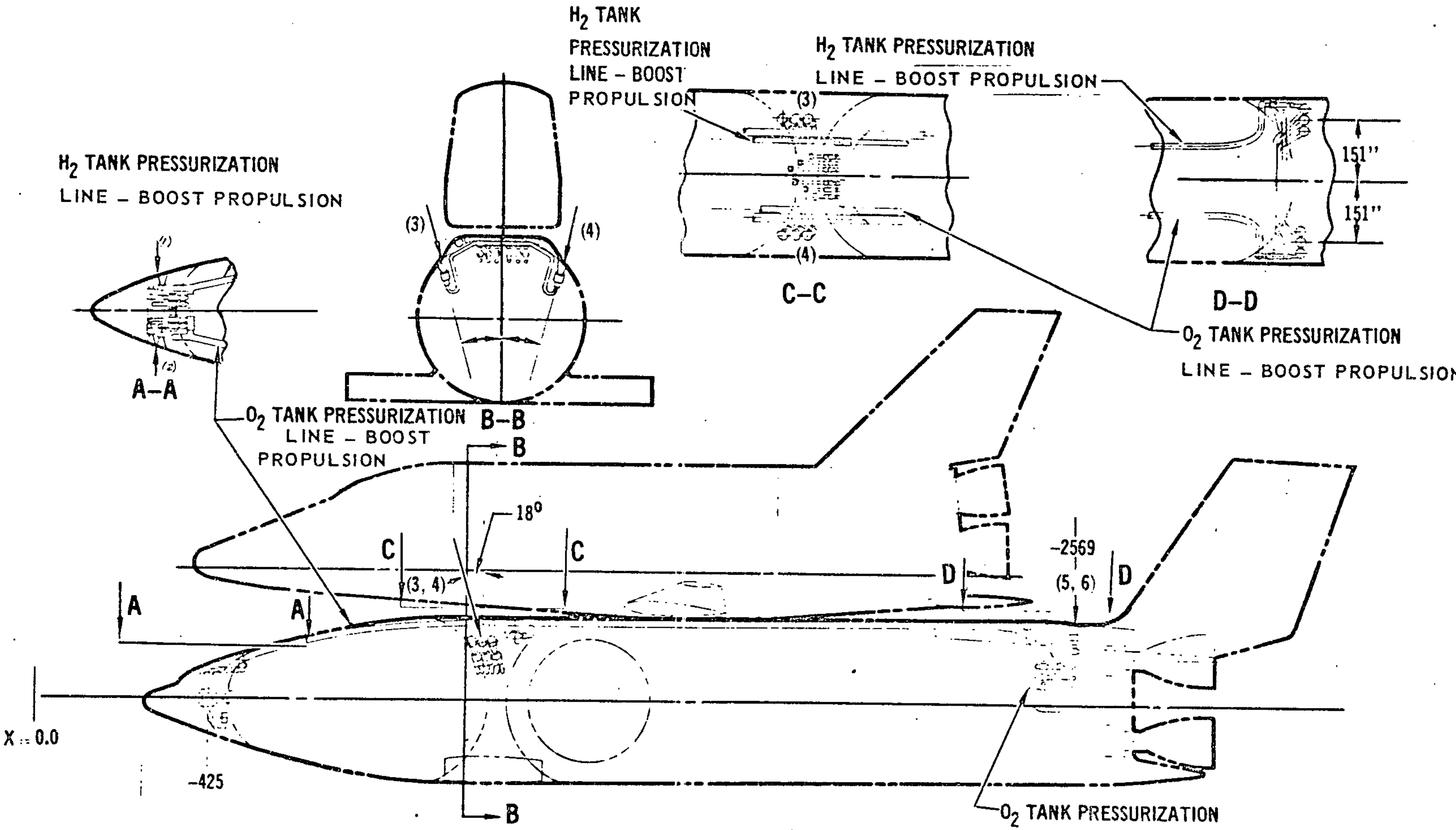
THRUST - LB	1080
CHAMBER PRESSURE - LBF/IN^2A	13.7
MIXTURE RATIO	3:1
EXPANSION RATIO	8:1
INLET PRESSURE - $LBF/IN.^2A$	15.7
INLET TEMPERATURE - O_2/H_2 - ^oR	200/150
SPECIFIC IMPULSE - SEC	376.5
FLOW RATE (TOTAL) - LB/SEC	2.87
FUEL FILM COOLANT - %	15
CYCLE LIFE - CYCLES	100,000
WEIGHT - TOTAL - LB	77.0
- INJECTOR	38.7
- CHAMBER & NOZZLE	14.6
- PROPELLANT VALVES	15.7
- IGNITION & MISCELLANEOUS	8.0
DIMENSIONS - IN	
- OVERALL LENGTH	40.0
- THROAT DIAMETER	8.0
- INSIDE CHAMBER DIAMETER	13.0
- NOZZLE EXIT DIAMETER (O.D.)	24.0
- INTERFACE DIAMETER	19.0
- VALVE EQUIVALENT FLOW AREA - IN^2 (O_2/H_2)	4.15/4.90

ORBITER APS ENGINE DESIGN CHARACTERISTICS

FIGURE 4-33

is shown in Figure 4-36, and consists of a stainless steel tube 100 in. long and 0.75 in. in diameter. One heat exchanger is required per main engine. Heat exchanger weight for all twelve engines is 57 lb and the increased hydrogen vapor residual weight is 660 lb. Both have been assessed against the APS as weight penalties.

Main Engine Tank Liquid/Vapor Separators (Booster) - The booster APS requires a minimum of 1000 lb of liquid residuals in each propellant tank to maintain tank pressures above 15-16 lb/in^2a upon completion of the mission profile (Figure 4-37). To ensure that only gases are extracted for APS operation, liquid/vapor separation valves are located at the APS gas inlets, as shown in Figure 4-38. During the booster mission a zero g propellant configuration will not occur; liquid propellants will either be in contact with the wall or reacting to imposed acceleration loads. A tank standoff prevents the outlet from being submerged by liquids in contact with the wall, while the low friction, g-sensitive valve closes the outlet when acceleration forces cause bulk liquid to move toward it, thus ensuring only acquisition of propellant vapor. Valve weights are 63 lb and 78 lb for the oxygen and hydrogen tanks, respectively.



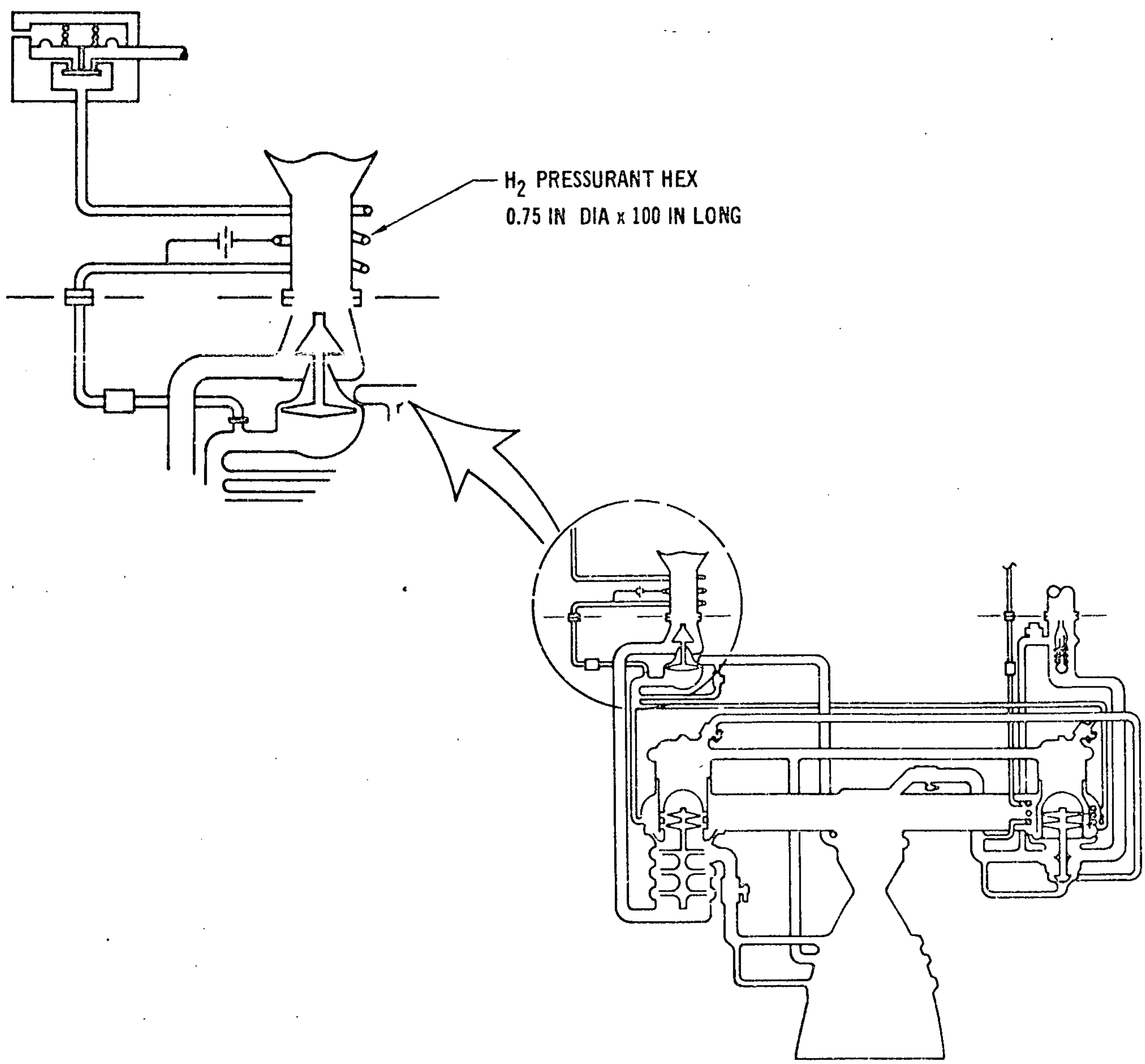
INSTALLATION – LOW PRESSURE AUXILIARY PROPULSION SUBSYSTEM – BOOSTER

FIGURE 4-34

	O_2	H_2
MAIN TANK		
INITIAL VAPOR TEMPERATURE, °R	520	260
INITIAL PRESSURE, LBF/IN^{2}A	26	26
MINIMUM PRESSURE, LBF/IN^{2}A	17	17
ENGINE AND DISTRIBUTION ASSEMBLIES		
DESIGN ENGINE INLET PRESSURE, LBF/IN^{2}A	14	14
DESIGN ENGINE INLET TEMPERATURE, °R	400	150
ENGINE THRUST, LB	2500	
MIXTURE RATIO	2:1	
CHAMBER PRESSURE, LBF/IN^{2}A	11	
EXPANSION RATIO	2:1	

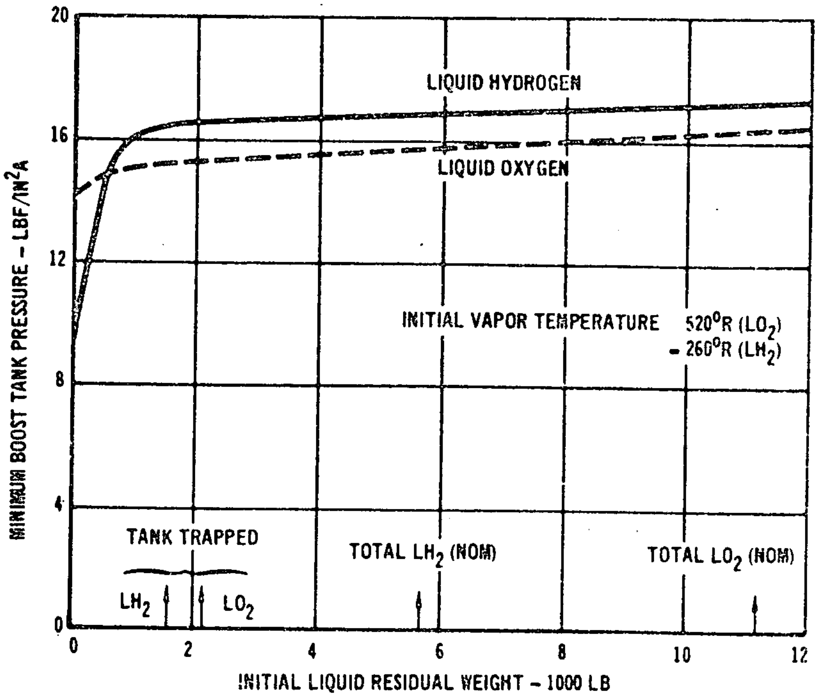
BOOSTER BASELINE DESIGN SUMMARY

FIGURE 4-35



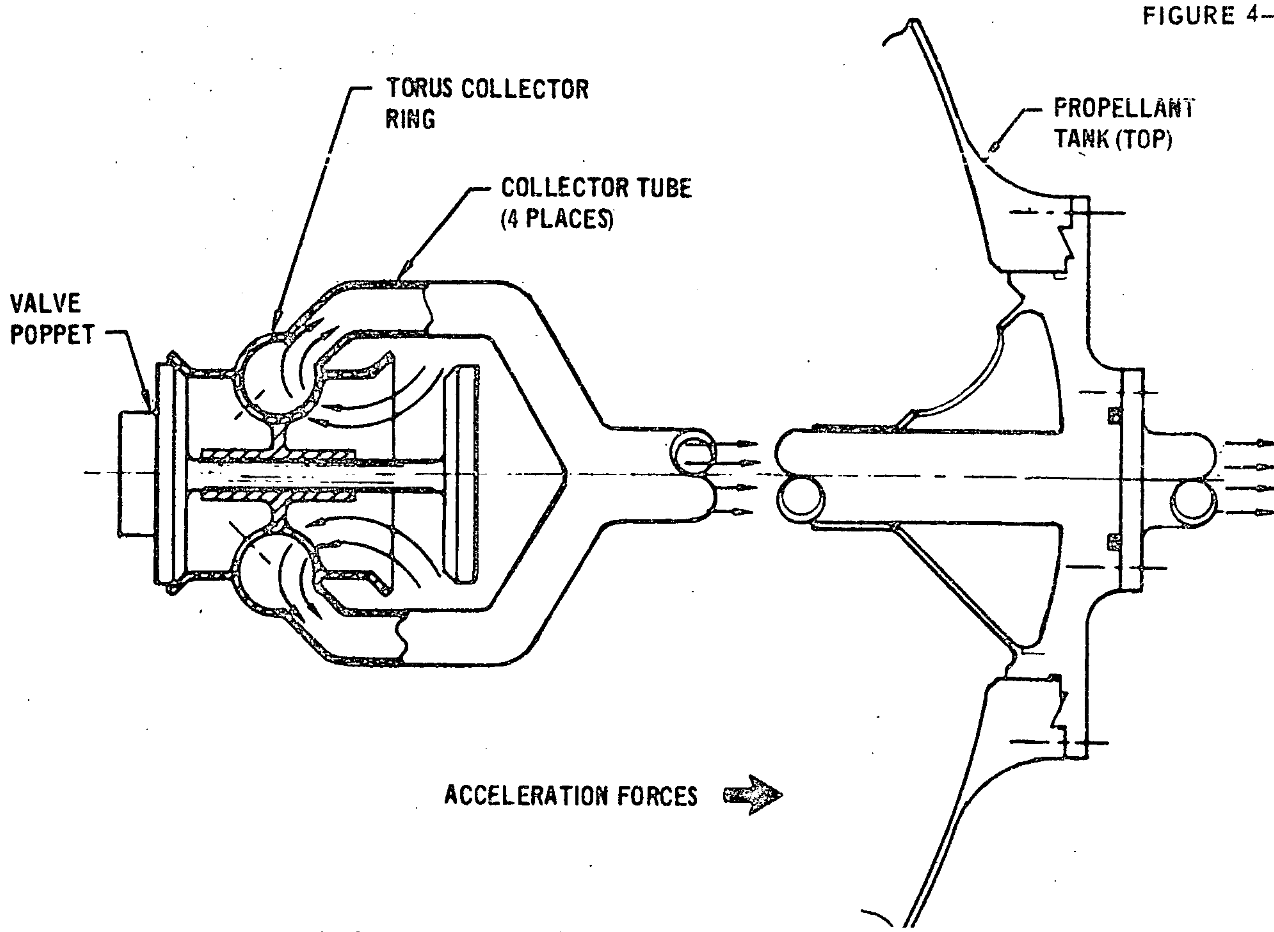
BOOSTER H_2 PRESSURANT HEAT EXCHANGER

FIGURE 4-36



SENSITIVITY OF BOOSTER MAIN TANK PRESSURE TO LIQUID RESIDUAL WEIGHT

FIGURE 4–37



BOOSTER MAIN ENGINE TANK OUTLET VALVE
(G SENSITIVE VALVE POPPET)

FIGURE 4–38

Propellant Distribution Assembly (Booster) - The propellant distribution assembly supplies propellant from main engine tanks to control engine assemblies and provides isolation of engines in case of failure. Figure 4-34 illustrates the distribution assembly installation. The assembly is composed of ducts, isolation valves, and linear and angular compensators. Booster and orbiter distribution assemblies are similar in design (the reader is referred to Section 4.1 for design approach and detail).

Booster APS line routing and valving are typified by the oxygen distribution assembly shown in schematic Figure 4-39. As in the case of the orbiter, main engine tank pressurization lines are used as APS trunklines. These lines are 18 in. in diameter and extend the full length of the booster vehicle. Remaining line diameters and lengths are given in Figure 4-39. As for the orbiter APS, booster APS propellant supply line diameters were sized to minimize overall APS weight. Design characteristics of the booster network are given in Figure 4-21. All lines and compensators are fabricated from 2219 aluminum and visor-type isolation valves are used throughout.

Component weight (lb) for oxidizer and fuel distribution networks are:

Lines	577
Linear Compensators	355
Angular Compensators	169
TOTAL	1101

Total isolation valve weight is 607 lb.

Engine Assemblies (Booster) - APS engine assemblies provide all attitude control for the space shuttle booster. Twenty 2500 lb thrust engines are used in the subsystem. Engine delivered specific impulse is 342 seconds, vacuum. Except for size, the booster engine assembly is similar to the orbiter APS engine discussed in Section 4.1 and shown in Figure 4-23. The nozzle expansion ratio optimized at 2:1 and a 15 degree divergence cone was used to minimize losses. Figure 4-40 presents valve design criteria, and Figure 4-41 the valve pneumatic actuation requirements. Gaseous helium requirements are 7.95×10^{-4} lb per valve cycle. Total booster APS helium requirements are 3.5 lb. The pneumatic subassembly schematic is shown in Figure 4-42. The helium is stored at 3500 lbf/in^{2}a in three titanium tanks, and is regulated to 370 lbf/in^{2}a to provide a valve opening response of 50 ms. A single solenoid pilot valve provides simultaneous actuation of both propellant engine valves. Total pneumatic subassembly weight is 101 lb.

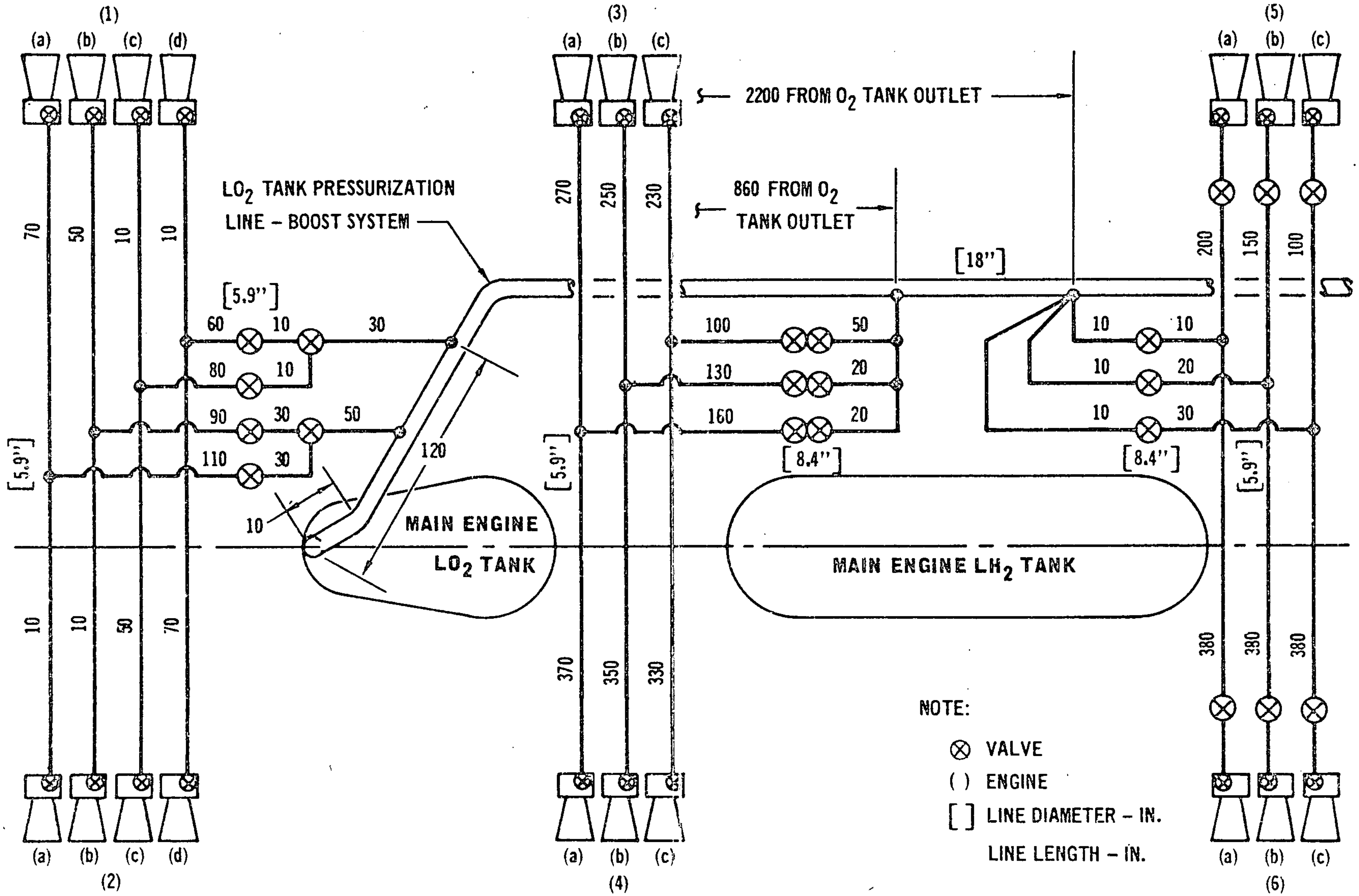


FIGURE 4-39

DISTRIBUTION NETWORK BOOSTER
(Oxygen Side)

	FUEL	OXIDIZER
FLOWRATE, LB/SEC	2.165	4.335
PRESSURE DIFFERENTIAL, LB/IN^2 d	1	1
TEMPERATURE, INLET, °R	160	400
EQUIVALENT FLOW DIAMETER, IN.	4.72	4.20
CYCLE LIFE	100/MISSION	100/MISSION
ACTUATION TYPE	PNEUMATIC	PNEUMATIC
RESPONSE GOAL	0.030/0.050	0.030/0.050
WEIGHT - LB		
VALVES	16.7	15.4
PILOT VALVE	2.5	-

DESIGN CRITERIA FOR BOOSTER ENGINE VALVES

FIGURE 4-40

PRESSURE REQUIRED, LBF/IN^2	370
VALVE SEALING ELEMENT SEAT LOAD, LB	565
ACTUATOR PISTON EFFECTIVE AREA, IN^2	3.4
CLOSING SPRING FORCE, LB	600
PISTON STROKE, IN	1.875
FRICTION FORCE, LB	242
GASEOUS HELIUM REQUIRED PER VALVE CYCLE, LB	0.0795×10^{-2}
PILOT VALVE EQUIVALENT FLOW DIA INCHES	0.375

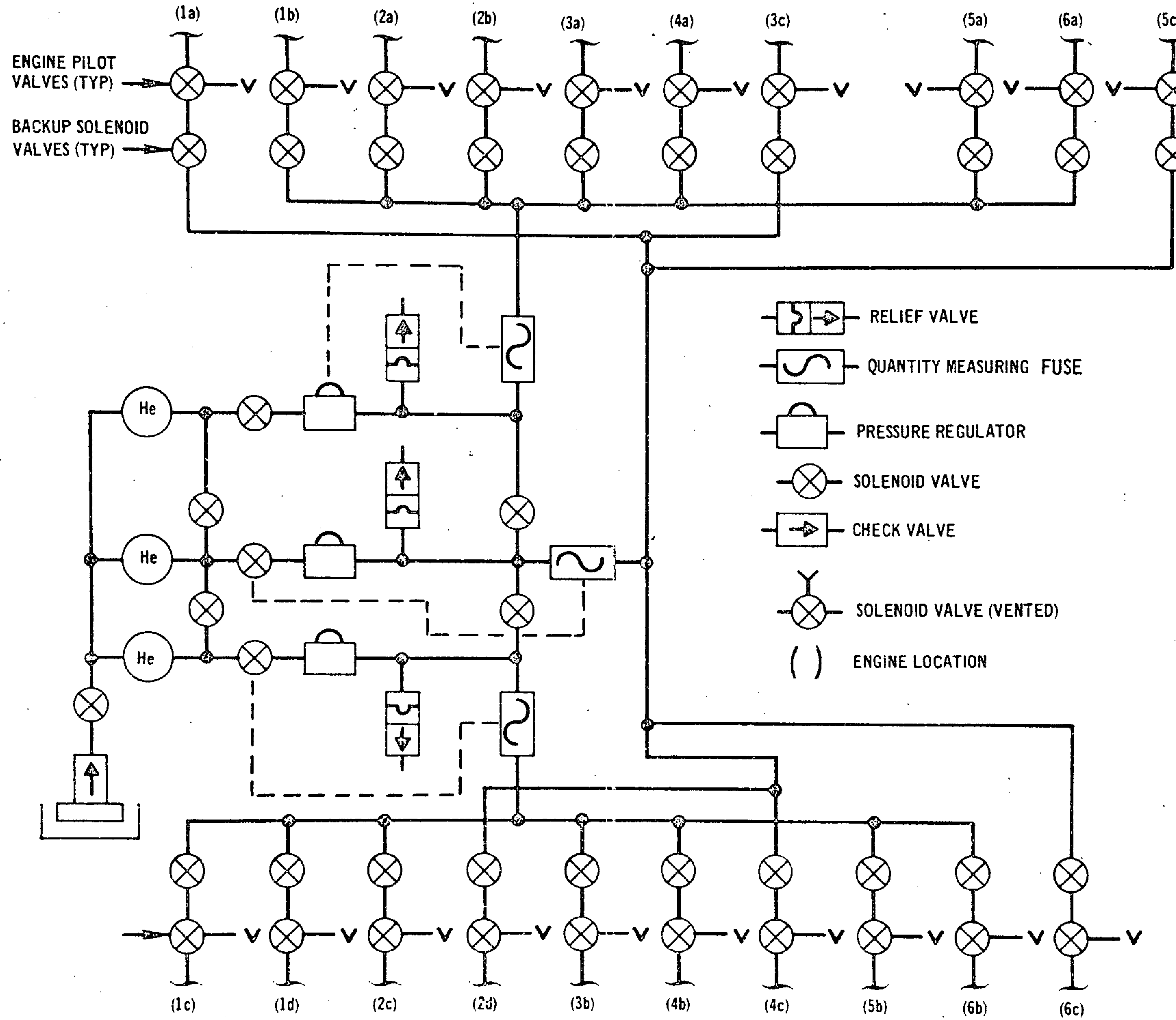
BOOSTER APS PNEUMATIC ACTUATION REQUIREMENTS
Engine Coaxial Poppet Valve

FIGURE 4-41

Engine performance (i.e., mixture ratio, chamber pressure, vacuum thrust, and vacuum specific impulse) sensitivity to inlet conditions (temperature and pressure) are shown in Figures 4-43 through 4-46. Nominal engine operating conditions are:

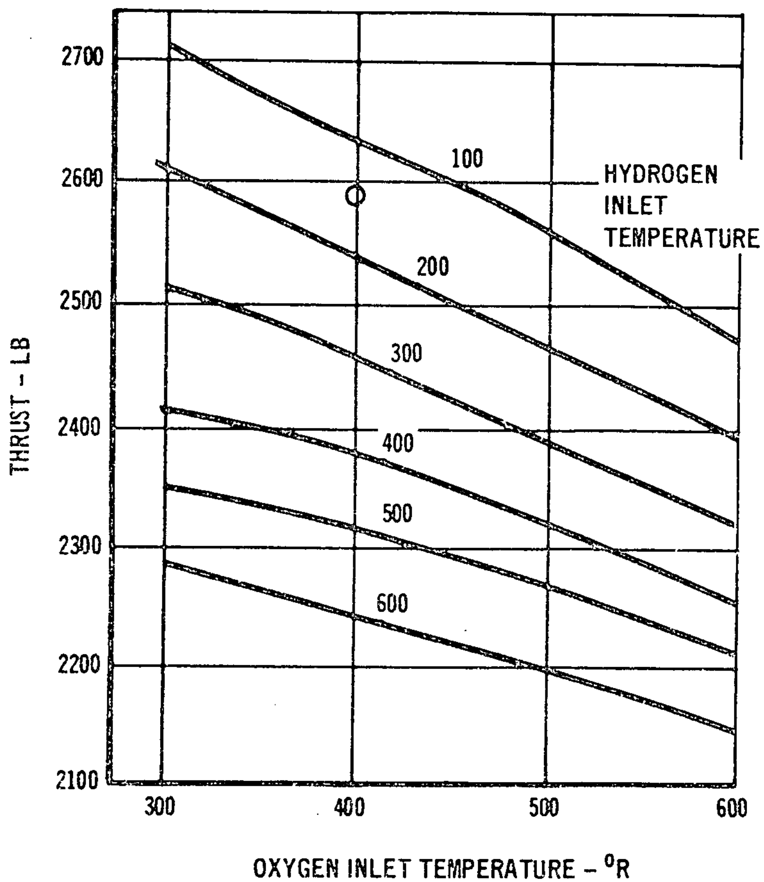
inlet pressure, lbf/in^2a	14.0
inlet temperature, °R	400 (O_2)
	150 (H_2)
chamber pressure, lbf/in^2a	11.0
mixture ratio, (O/F)	2.0

Booster engine design conditions, component weights, and dimensions are summarized in Figure 4-47. Engine weight is 149 lb per assembly.



PNEUMATIC SUBASSEMBLY – ENGINE VALVE ACTUATION (Booster)

FIGURE 4-42



DESIGN CONDITIONS

THRUST	– 2500 LB
CHAMBER PRESSURE	– 11 LBF/IN^2 A
INLET PRESSURES	
O_2 AND H_2	– 14 LBF/IN^2 A
EXPANSION RATIO	– 2:1
MIXTURE RATIO	– 2:1
INLET TEMPERATURE	
GH_2	– 150°R
GO_2	– 400°R

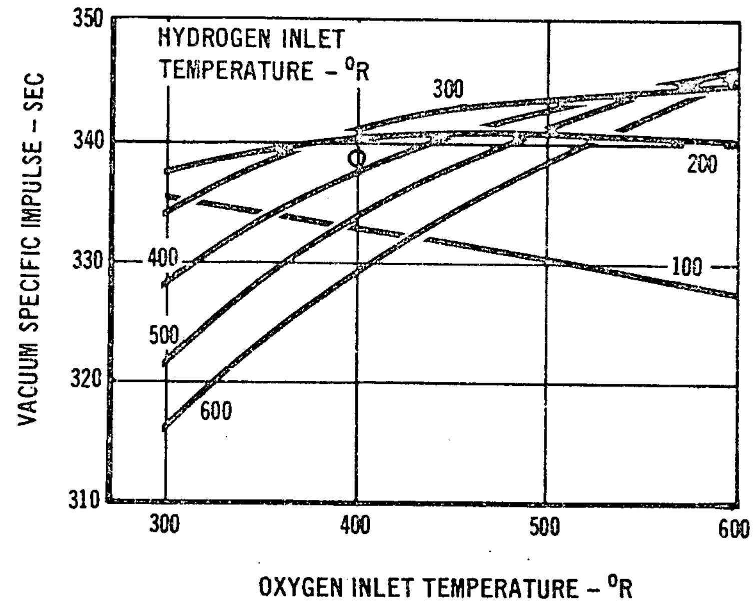
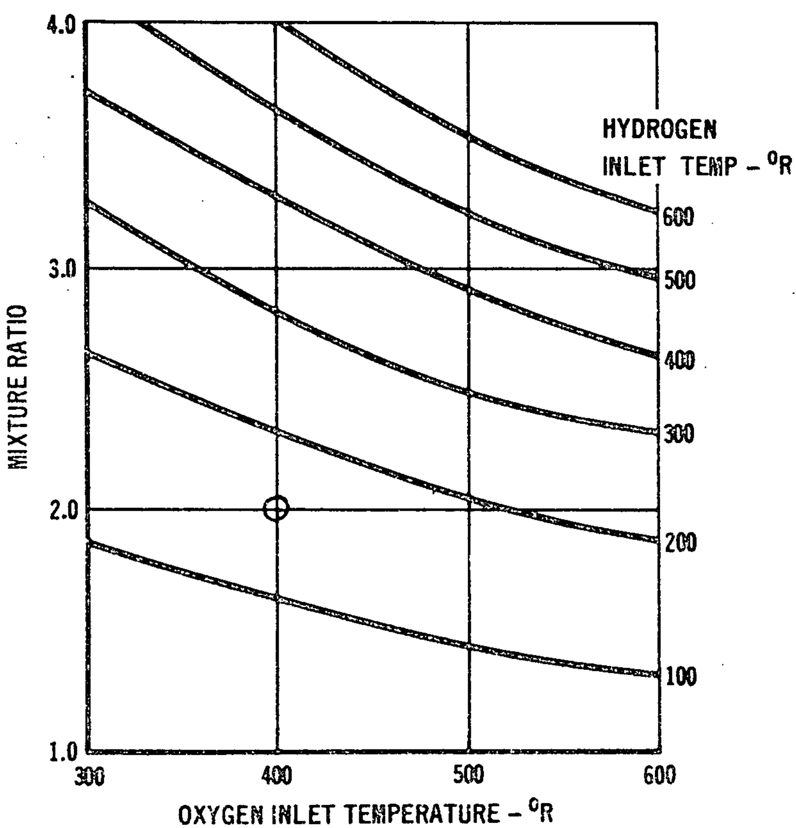


FIGURE 4-43

ENGINE PERFORMANCE SENSITIVITY TO INLET TEMPERATURE
(Booster)

DESIGN CONDITIONS

THRUST	– 2500 LB	MIXTURE RATIO	– 2:1
CHAMBER PRESSURE	– 11 LBF/IN^2 A	INLET TEMPERATURE	
INLET PRESSURES		GH_2	– 150°R
O_2 AND H_2	– 14 LBF/IN^2 A	GO_2	– 400°R
EXPANSION RATIO	– 2:1		



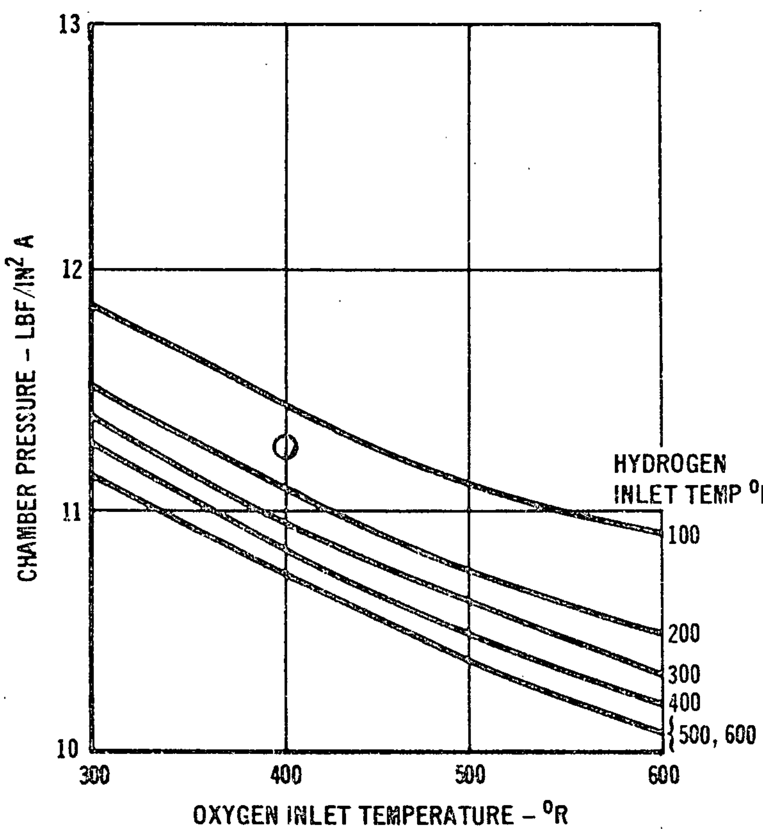
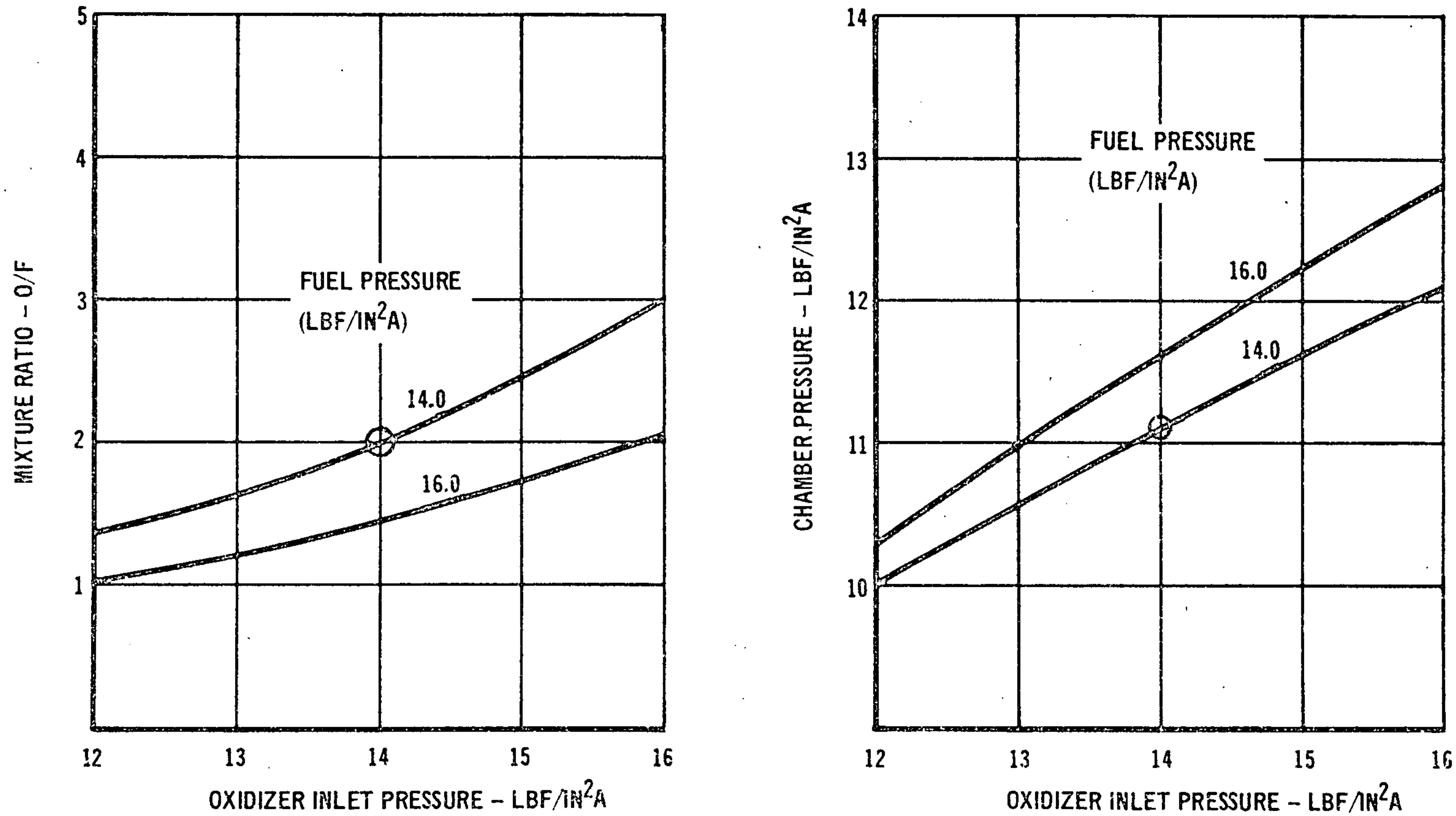


FIGURE 4-44

ENGINE PERFORMANCE SENSITIVITY TO INLET TEMPERATURE
(Booster)

DESIGN POINT

$F = 2500$ LB
$P_c = 11$ LBF/IN^{2}A
$MR = 2:1$
$\epsilon = 2:1$
$T_{INLET} = 150^0R\ (H_2)$
$400^0R\ (O_2)$

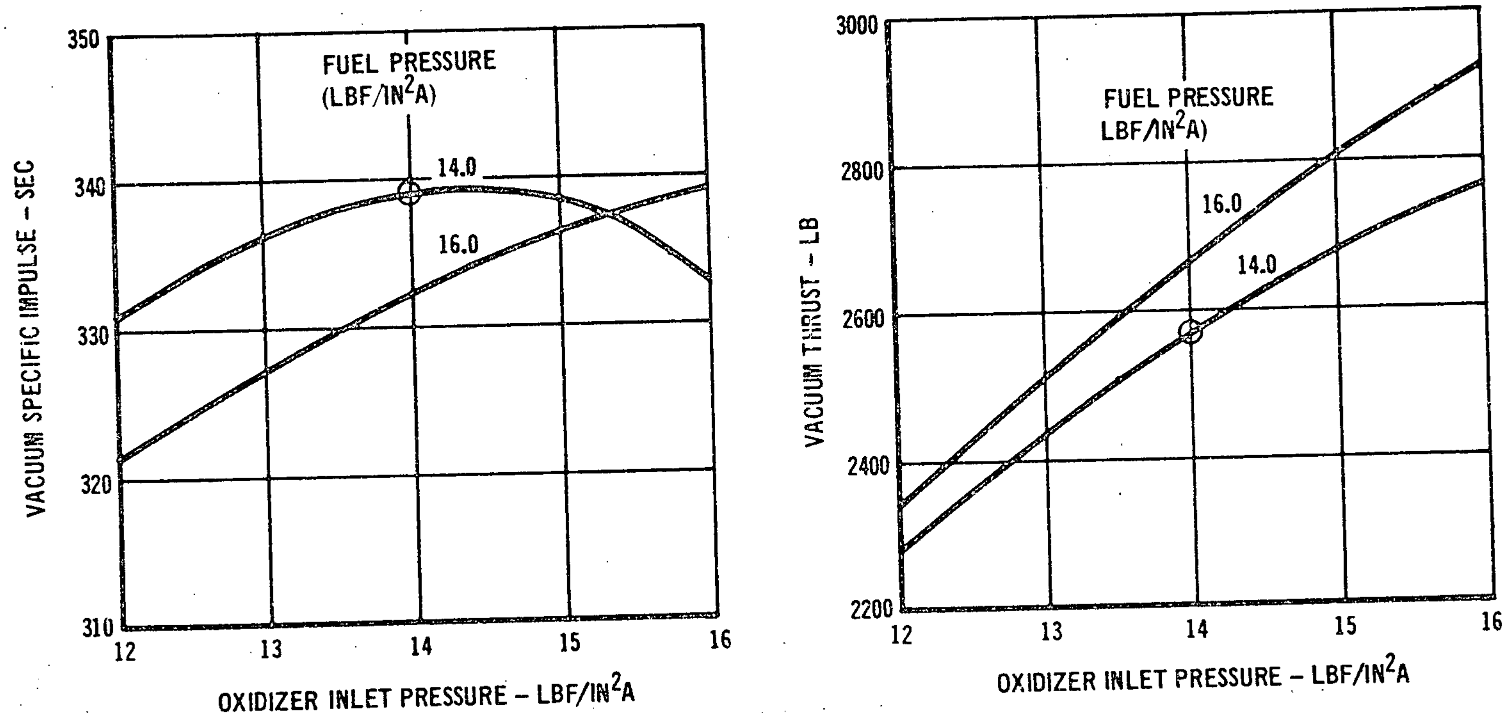


ENGINE PERFORMANCE SENSITIVITY TO INLET PRESSURE
(Booster)

FIGURE 4-45

DESIGN POINT

F = 2500 LB
P_c = 11 LBF/IN^{2}A
MR = 2:1
ϵ = 2:1
T_{INLET} = 150^{0}R (H_2)
400^{0}R (O_2)



ENGINE PERFORMANCE SENSITIVITY TO INLET PRESSURE
(Booster)

FIGURE 4-46

THRUST	– LB	2500
CHAMBER PRESSURE	– LBF/IN.^{2}A	11.0
MIXTURE RATIO		2:1
EXPANSION RATIO		2:1
INLET PRESSURE	– LBF/IN.^{2}A	14.0
INLET TEMPERATURE	– O_2/H_2 – ^oR	400/150
SPECIFIC IMPULSE	– SECS	342
FLOW RATE TOTAL	– LB/SEC	7.31
FUEL FILM COOLANT	– %	10
CYCLE LIFE	– CYCLES	100,000
WEIGHT – TOTAL	LB	149.0
– INJECTOR		83.1
– CHAMBER & NOZZLE		22.3
– PROPELLANT VALVES		34.6
– IGNITION & MISCELLANEOUS		9.0
DIMENSIONS	– IN.	
– OVERALL LENGTH		45.0
–THROAT DIAMETER		14.2
– INSIDE CHAMBER DIAMETER		23.2
– NOZZLE EXIT DIAMETER (O.D.)		22.0
– INTERFACE DIAMETER		34.0
– VALVE EQUIVALENT FLOW AREA – IN.^{2} (O_2/H_2)		13.2/16.6

BOOSTER APS ENGINE DESIGN CHARACTERISTICS

FIGURE 4-47

5. SUBSYSTEM PERFORMANCE

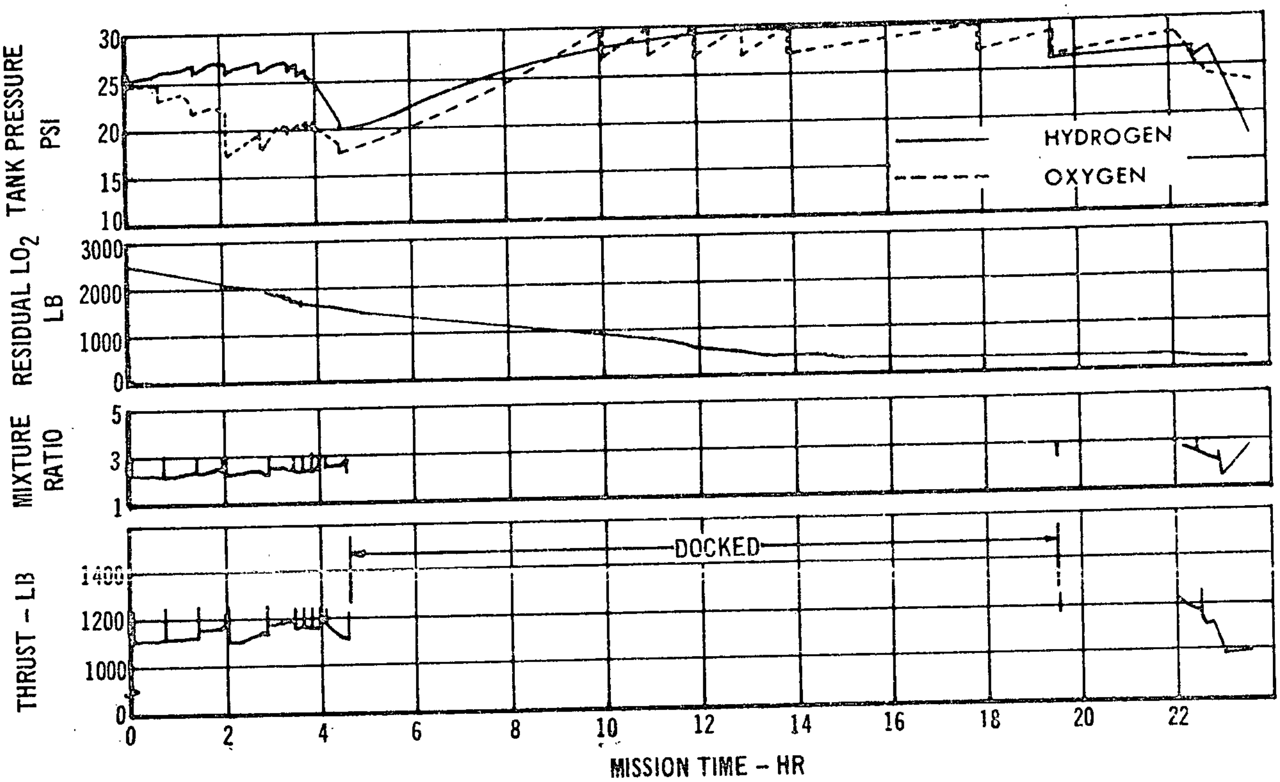
5.1 Mission Performance (Orbiter) - Orbiter APS performance for third and seventeenth orbit rendezvous missions is shown in Figures 5-1 and 5-2, respectively. Oxidizer and fuel main engine tank vapor pressures are shown for the entire, mixed mode, mission duty cycle. Also shown are compartmented tank residual-liquid and vapor, mixture ratio, and engine thrust-time histories. Satisfactory performance is obtained for both rendezvous missions. During a major APS operation, engine inlet conditions are controlled by addition of liquid propellant to the mixer, providing a constant thrust level of 1080 lb per engine at a mixture ratio of 3.0. The controlled conditions are 15.7 lbf/in^2a pressure and temperatures of 200°R (O_2) and 150°R (H_2).

The effect of environmental temperature extremes on APS mission performance was evaluated for the mission imposing the most stringent APS requirements, viz., the seventeenth orbit rendezvous. Hydrogen and oxygen main engine tank vapor pressure time histories are shown in Figure 5-3 for environmental temperatures of 460° and 600°R. These values represent realistic tank temperature extremes, as defined by orbiter thermal environment analysis. Resupply propellant requirements are also tabulated in Figure 5-3 for the two environmental temperatures. Oxidizer and fuel tankage requirements are reduced approximately 2 percent as the environmental temperature is decreased from 600° to 460°R due to lower propellant vent losses. APS tankage is based on the more stringent 600°R requirements.

The sensitivity of resupply propellant tankage requirements to initial propellant vapor state is shown in Figure 5-4 for the seventeenth orbit rendezvous mission. Variations in both initial vapor temperatures and pressures were investigated. As Figure 5-4 demonstrates, hydrogen and oxygen APS tankage requirements are relatively insensitive to initial main engine tank vapor conditions.

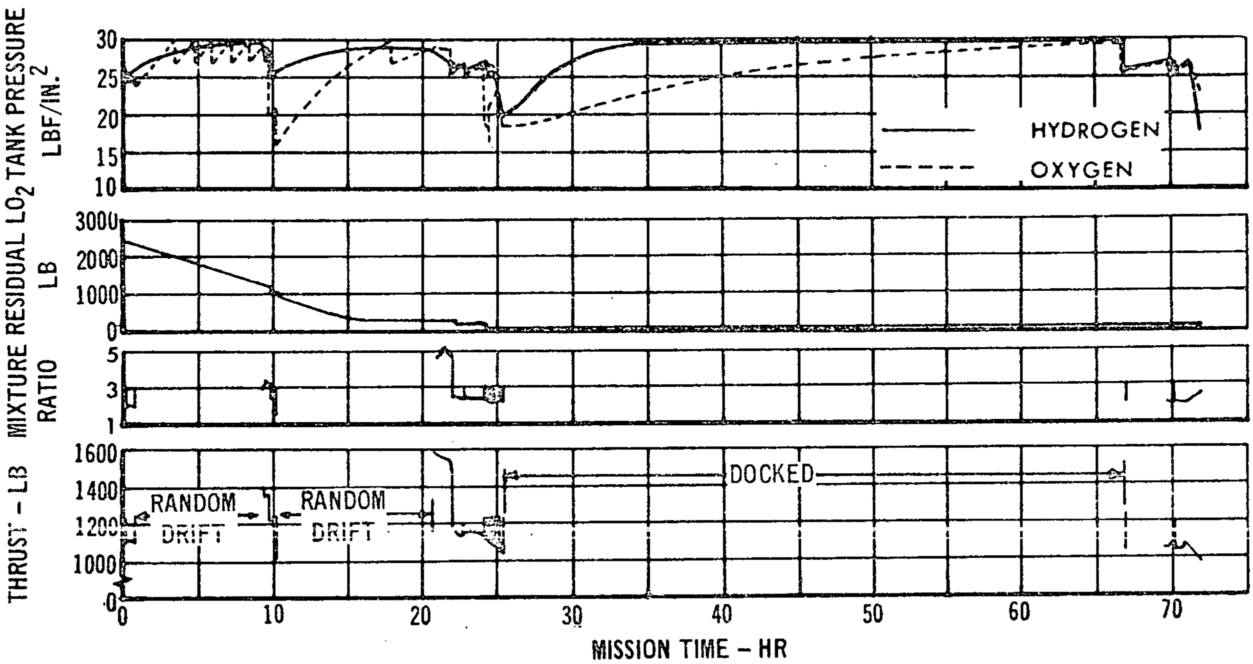
For APS pulse mode operation, the effect of propellant inlet temperatures on engine minimum impulse bit (MIB) is shown in Figure 5-5. As shown, the MIB is less than 70 lb-sec for oxygen inlet temperatures in excess of 260°R. Typical values of pulse mode MIB are 61 to 67 lb-sec, since, for limit cycle operation, all propellant is extracted from main engine tanks and will be relatively warm.

5.2 Mission Performance (Booster) - The booster APS provides damping of both engine shutdown and vehicle separation transients, and orients and controls the



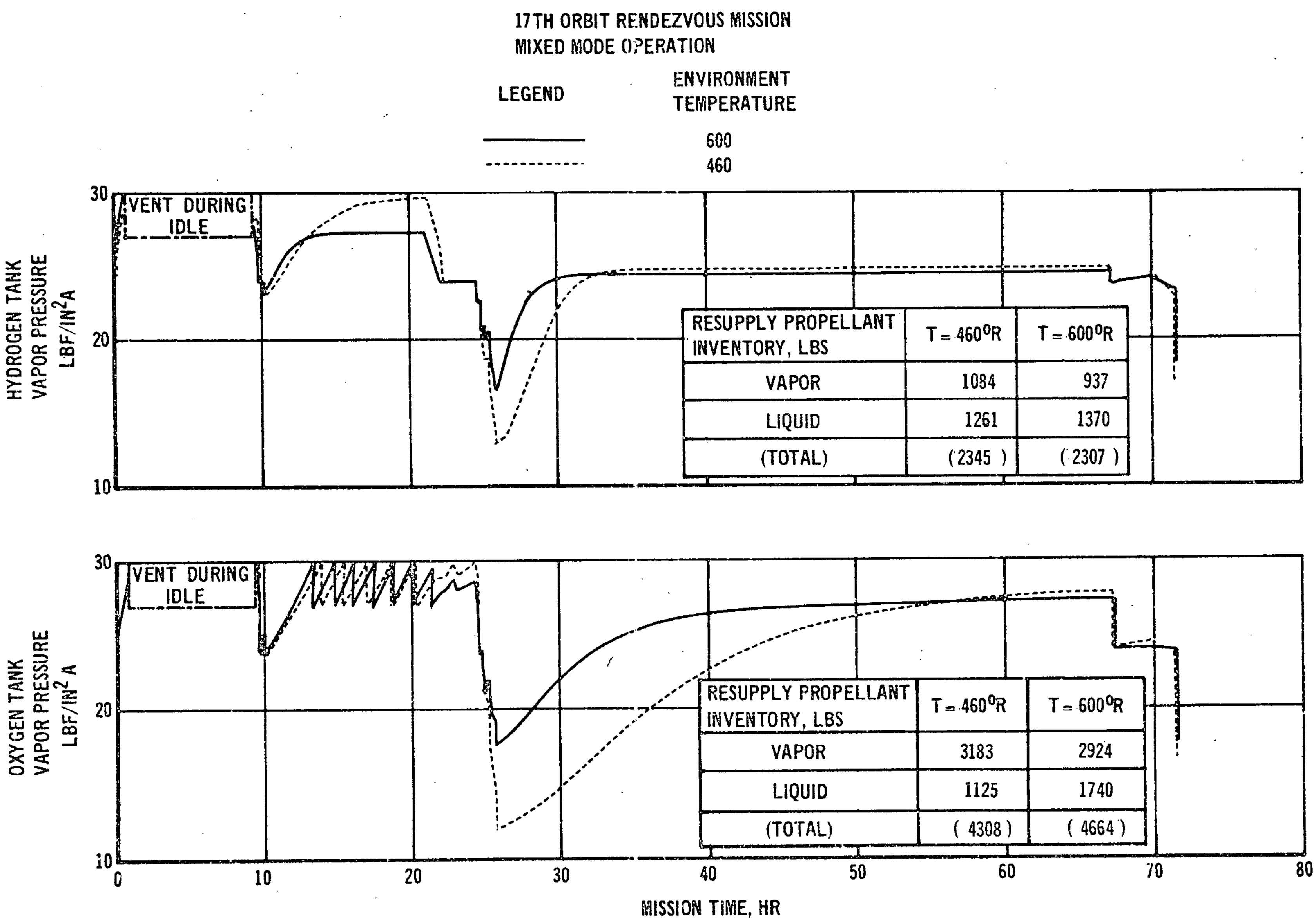
ORBITER MISSION DUTY CYCLE – 3RD ORBIT RENDEZVOUS

FIGURE 5-1



ORBITER MISSION DUTY CYCLE – 17TH ORBIT RENDEZVOUS

FIGURE 5-2



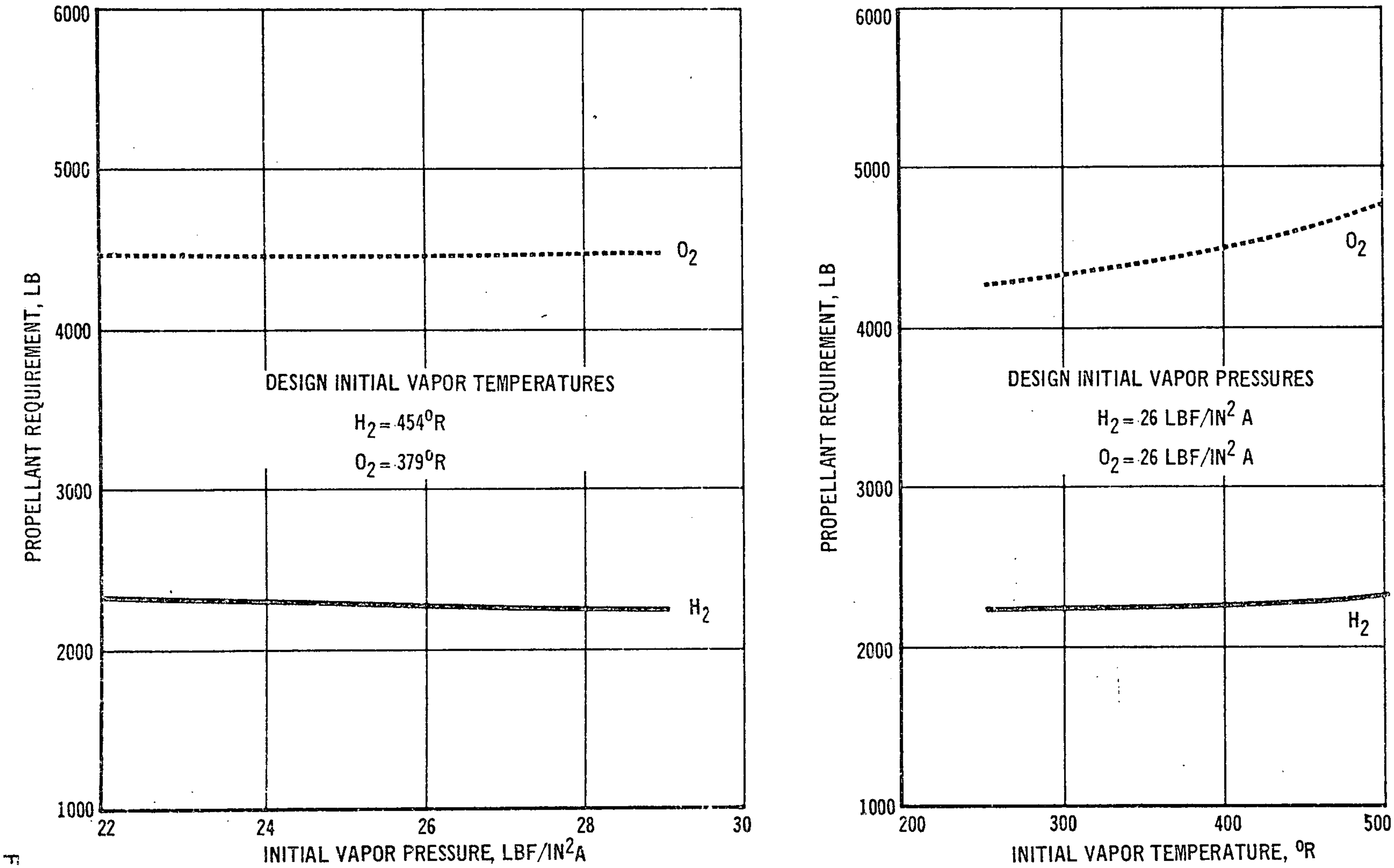
RESUPPLY PROPELLANT INVENTORY, LBS	$T = 460^oR$	$T = 600^oR$
VAPOR	1084	937
LIQUID	1261	1370
(TOTAL)	(2345)	(2307)

RESUPPLY PROPELLANT INVENTORY, LBS	$T = 460^oR$	$T = 600^oR$
VAPOR	3183	2924
LIQUID	1125	1740
(TOTAL)	(4308)	(4664)

EFFECT OF ENVIRONMENTAL TEMPERATURE EXTREMES

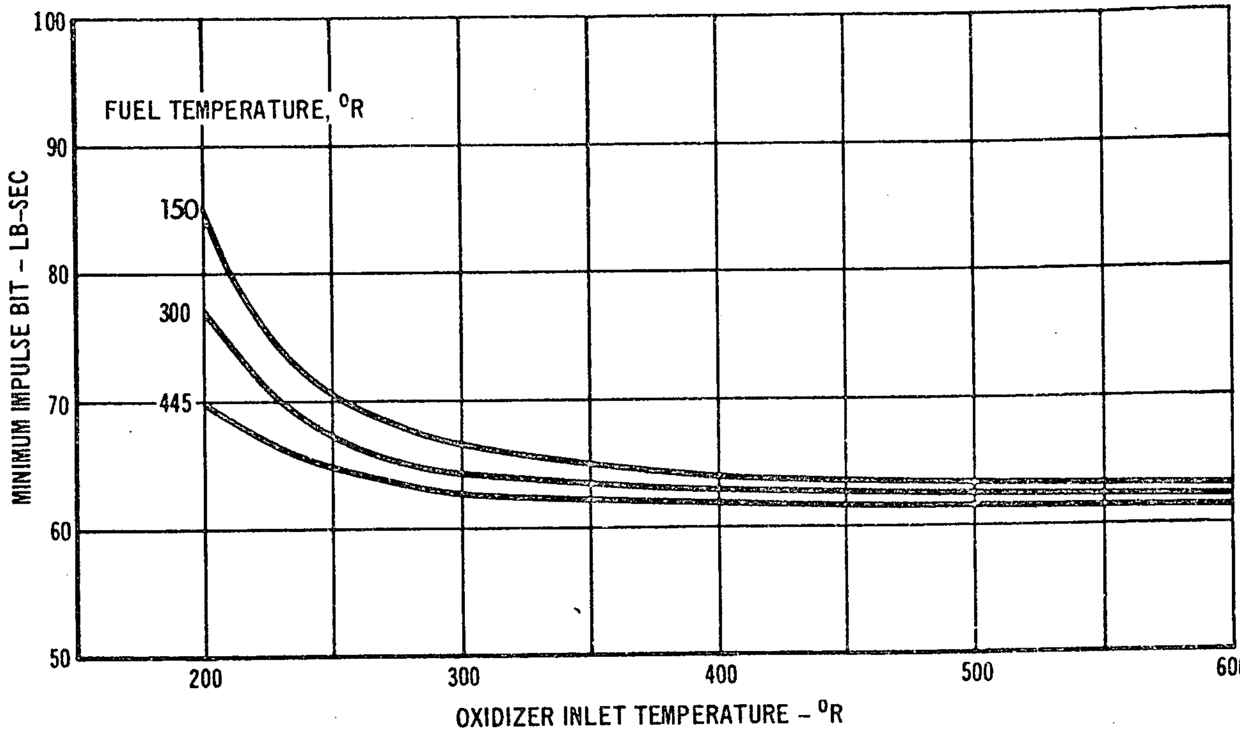
FIGURE 5-3

NOTE: SENSITIVITY TO INITIAL PROPELLANT VAPOR STATE
17TH ORBIT RENDEZVOUS MISSION
DESIGN MIXTURE RATIO = 3



ORBITER APS PROPELLANT REQUIREMENTS

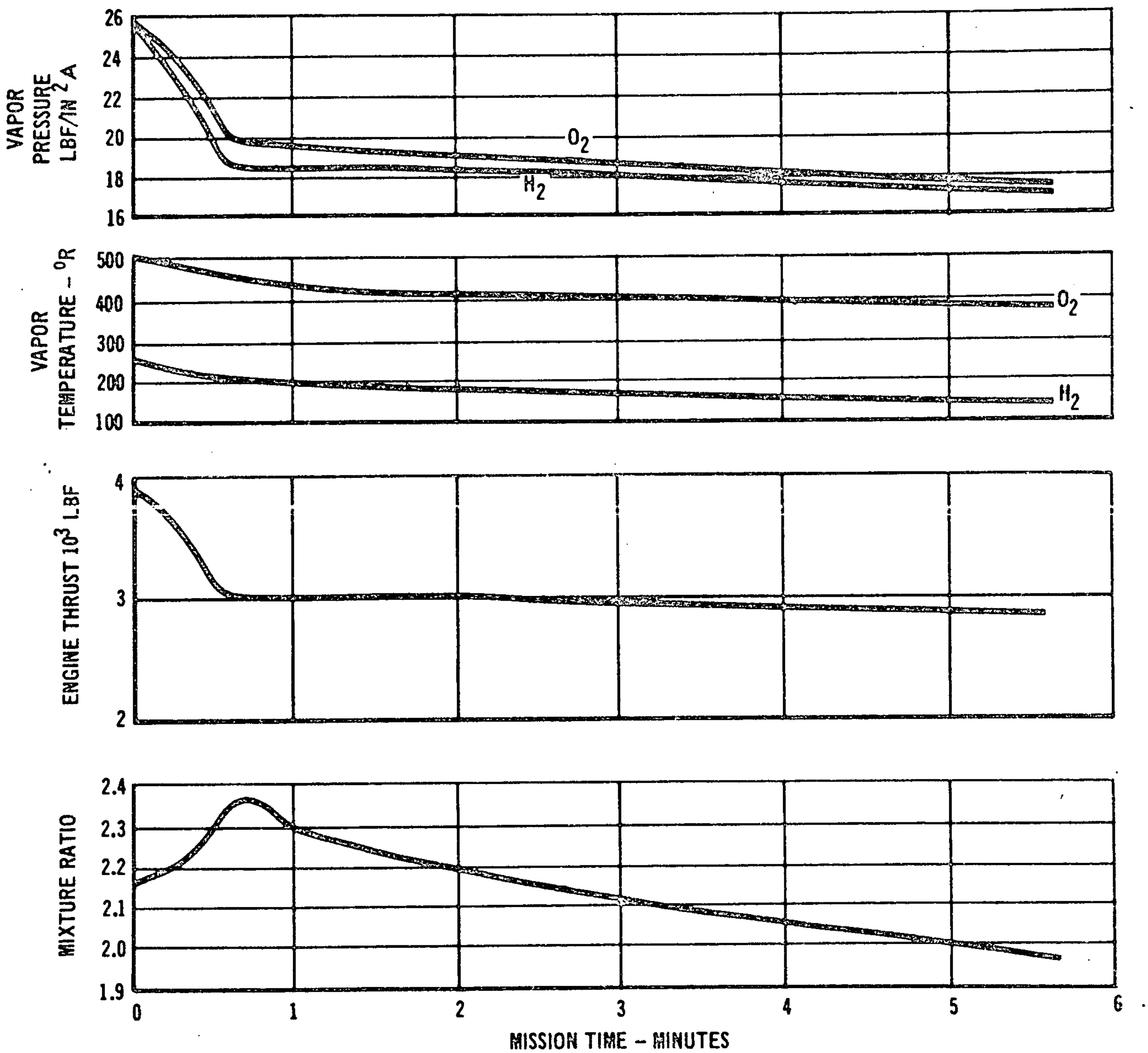
FIGURE 5-4



SENSITIVITY OF MIB TO INLET TEMPERATURE - ORBITER APS ENGINES
FIGURE 5-5

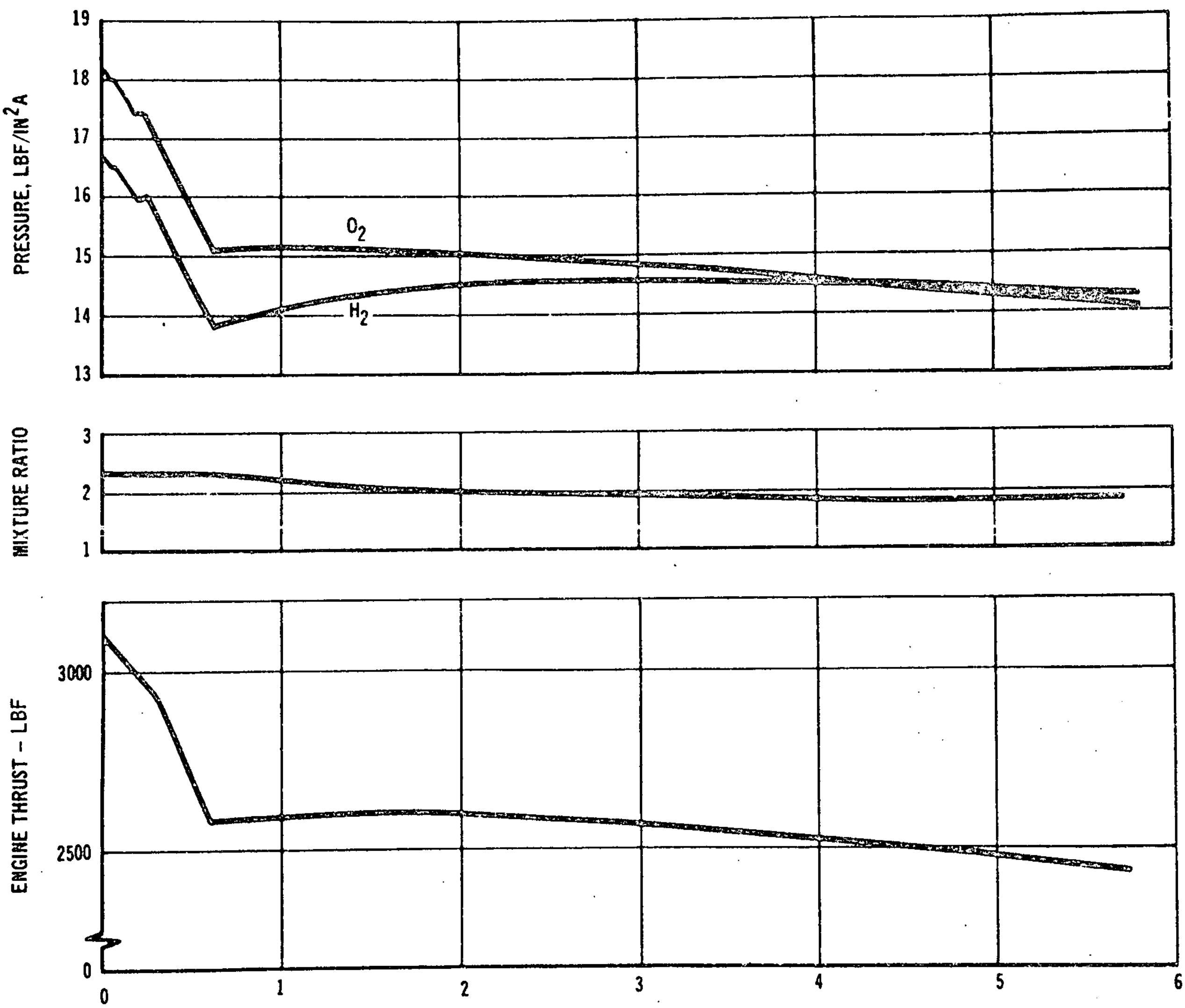
booster vehicle during reentry. Total mission time is approximately 5 minutes and APS total impulse expenditure is 864K lb-sec. The booster APS mission operating characteristics are shown in Figure 5-6 for nominal initial tank ullage pressures of 26 lbf/in^{2}a and temperatures of 520°R (O_2) and 260°R (H_2). Main engine tank temperature and pressure histories, and their resultant effect on engine performance (thrust and mixture ratio), are shown for the entire APS operation. Main tank pressures do not decay below the minimum operating pressure of 17 lbf/in^{2}a required for reasonable subsystem margins, and tank vapor temperatures are within the limits required for good engine ignition and performance. Over the mission duty cycle, thrust levels varied from 3780 to 2800 lb, well above the engine design point of 2500 lb., and mixture ratio varied from 2.34 to 1.99 compared to the design condition of 2.0.

Mixing of main engine tank liquid and vapor residuals at main engine shutdown could cause a significant change in propellant initial conditions. APS performance for complete equilibration (mixing) of tank-trapped residuals is shown in Figure 5-7. As illustrated, engine performance is deemed totally satisfactory.



BOOSTER APS MISSION OPERATING CHARACTERISTICS

FIGURE 5–6



BOOSTER APS PERFORMANCE
(Equilibrated Main Tank Propellant Residuals)

FIGURE 5-7

6. SUBSYSTEM WEIGHT

6.1 Weight Summary (Orbiter) - The orbiter APS weight breakdown is presented in Figure 6-1. Subtotal weights are shown for APS propellant, main engine propulsion modifications, and the five primary assemblies. Propellant weight includes usable, vent, and APS residuals, but excludes main engine residuals of which 2182 lbs. of oxygen are used by the APS. Use of these residuals incurs a 50 lb weight penalty for the liquid/vapor separation device (the compartmented oxygen

COMPONENT (NO)	WEIGHT, LB	
	O_2	H_2
PROPELLANT (*)	**(4496)**	**(2499)**
MAIN PROPULSION MODS.	(92)	(42)
COMPARTMENTED TANK	50	–
PRESSURANT LINE BYPASS VALVES (2)	42	42
PROPELLANT STORAGE ASSEMBLY	**(233)**	**(820)**
TANK, INSULATION, AND VENT	**164**	**556**
PRESSURIZATION SUBASSEMBLY	**32**	**159**
PROPELLANT ACQUISITION	**37**	**105**
PROPELLANT CONDITIONING ASSEMBLY	(149)	(327)
LINE AND MANIFOLDS	37	64
TUBING	47	98
ATTACHMENT FLANGES	56	154
VALVES (5)	9	11
LIQUID/VAPOR MIXING ASSEMBLY	(96)	(108)
MIXER	17	11
THROTTLE VALVE	22	22
CONTROL VALVES (5)	44	55
REGULATORS (2)	13	20
DISTRIBUTION ASSEMBLY	(565)	(707)
LINES	174	258
COMPENSATORS, LINEAR	97	127
COMPENSATORS, ANGULAR	68	76
ISOLATION VALVES (24)	226	246
ENGINE ASSEMBLES	(2734)	
ENGINES (33)	2541	
PNEUMATIC SUBASSEMBLY		
HELIUM	11	
TANKS (3)	103	
VALVES (42)	19	
REGULATOR (5)	14	
LINES	46	
(TOTAL)	**(12,868)**	

* INCLUDES REQUIREMENTS FOR OMS PROPELLANT SETTLING (120,000 LB-SEC).

ORBITER APS WEIGHT

FIGURE 6-1

tank). As shown, the weight of the main propulsion subsystem was also increased by the addition of pressurant line bypass valves. Both weight penalties were assessed against the APS. A more detailed weight breakdown of the propellant storage assembly and engine assemblies are given in Figure 4-9 and 4-33 respectively. Total orbiter APS weight is 12868 lbs.

6.2 Weight Sensitivities (Orbiter) - Orbiter APS weight sensitivities about the design point are shown in Figure 6-2, including sensitivities to thrust, impulse, chamber pressure, mixture ratio, nozzle expansion ratio, main engine tank pressure, and propellant conditioning temperatures. As shown, for the cases where the main engine tank pressure exceeded the Reference (a) design pressure, associated tank weight penalties were charged to the APS. As indicated in Figure 6-2, subsystem weight is quite sensitive to increases in impulse and thrust levels.

6.3 Weight Summary (Booster) - The booster APS weight breakdown is presented in Figure 6-3. Subtotal weights are shown for the main engine propulsion modifications and for the two primary assemblies (distribution and engine assemblies). No APS propellant is required. Modification to the main engine propulsion subsystem incurs the following weight penalties:

(1) 660 pounds H_2 pressurant and 57 lb H_2 heat exchanger (both associated with reduction of residual H_2 vapor temperature)

(2) 141 lb for the liquid/vapor separation valves.

A detailed engine weight breakdown is given in Figure 4-47. Total booster APS weight is 5647 lbs.

6.4 Weight Sensitivities (Booster) - Booster APS weight sensitivities about the design point are shown in Figure 6-4. As is true for the orbiter, sensitivities to thrust, chamber pressure, mixture ratio, nozzle expansion ratio, and main engine tank pressure were determined, and main engine tank weight increases were assessed against APS weight for tank pressures exceeding the Reference (a) design point. Subsystem weight sensitivity to total impulse and resupply propellant conditioning temperatures are not applicable since sufficient main engine tank residual propellant is available for APS operation. Figure 6-4 shows subsystem weight to be very sensitive to thrust and chamber pressure, and relatively insensitive to mixture ratio and expansion ratio. The main engine tank weight sensitivity to maximum vent pressure reported in Reference (a) precludes using higher initial vapor pressures to reduce subsystem weight.

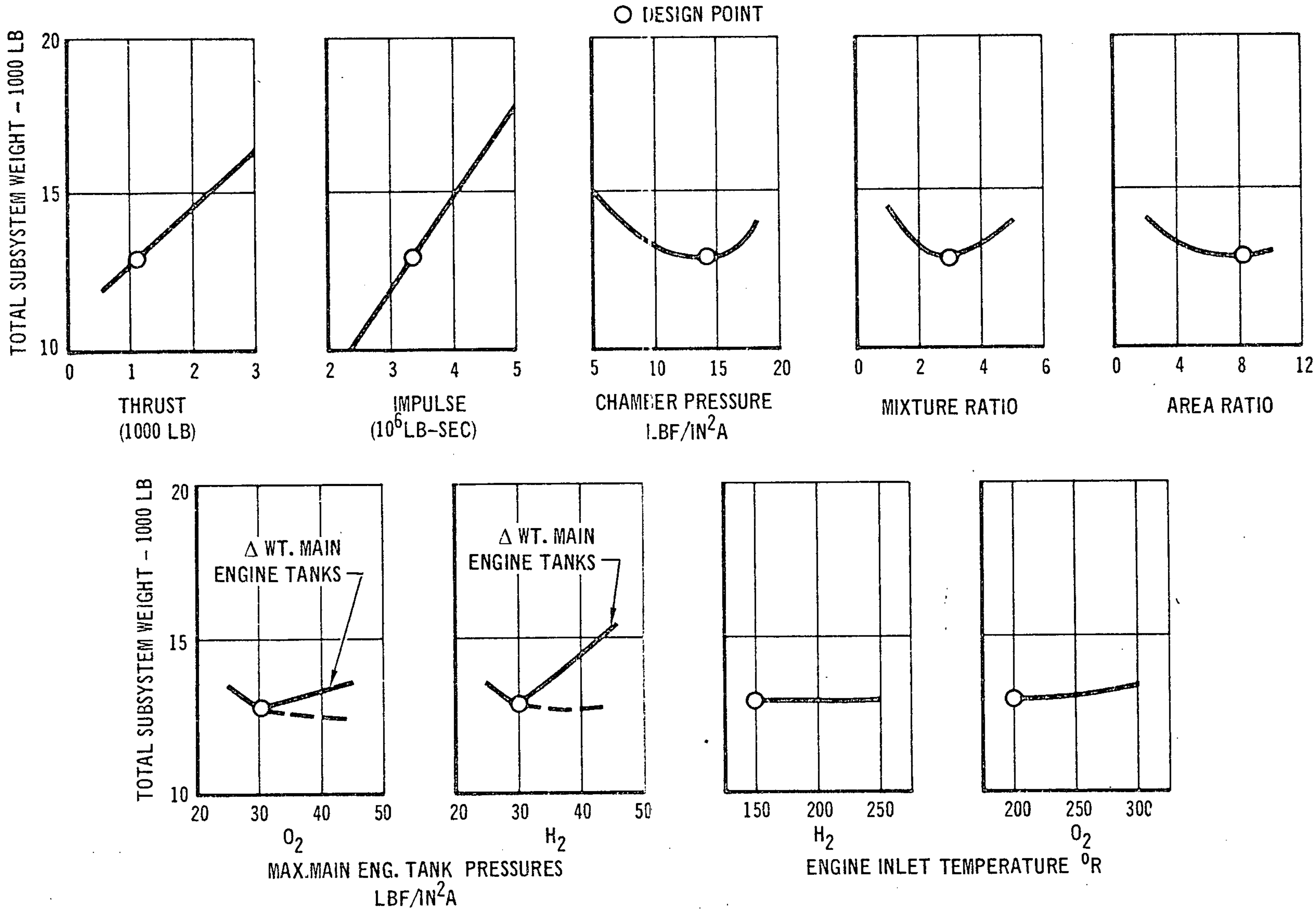


FIGURE 6-2

ORBITER APS WEIGHT SENSITIVITIES

COMPONENT (NO.)	WEIGHT, LB O_2	H_2
PROPELLANT	NONE REQUIRED, MAIN ENGINE TANK RESIDUALS ARE UTILIZED	
MAIN ENGINE PROPULSION MODS	(63)	(795)
PRESSURANT PENALTY	0	660
LIQUID/VAPOR SEPARATION VALVES (1)	63	78
HEAT EXCHANGER	0	57
PROPELLANT DISTRIBUTION ASSEMBLY	(657)	(1051)
LINES	227	350
COMPENSATORS, LINEAR (23)	104	251
COMPENSATORS, ANGULAR (46)	64	105
ISOLATION VALVES (21)	262	345
ENGINE ASSEMBLIES	(3081)	
ENGINES (20)	2980	
PNEUMATIC SUBASSEMBLY		
HELIUM	3.5	
TANKS (3)	34.0	
VALVES (28)	12.5	
REGULATORS (3)	9.0	
LINES	42	
TOTAL	(5647)	

BOOSTER APS WEIGHT

FIGURE 6-3

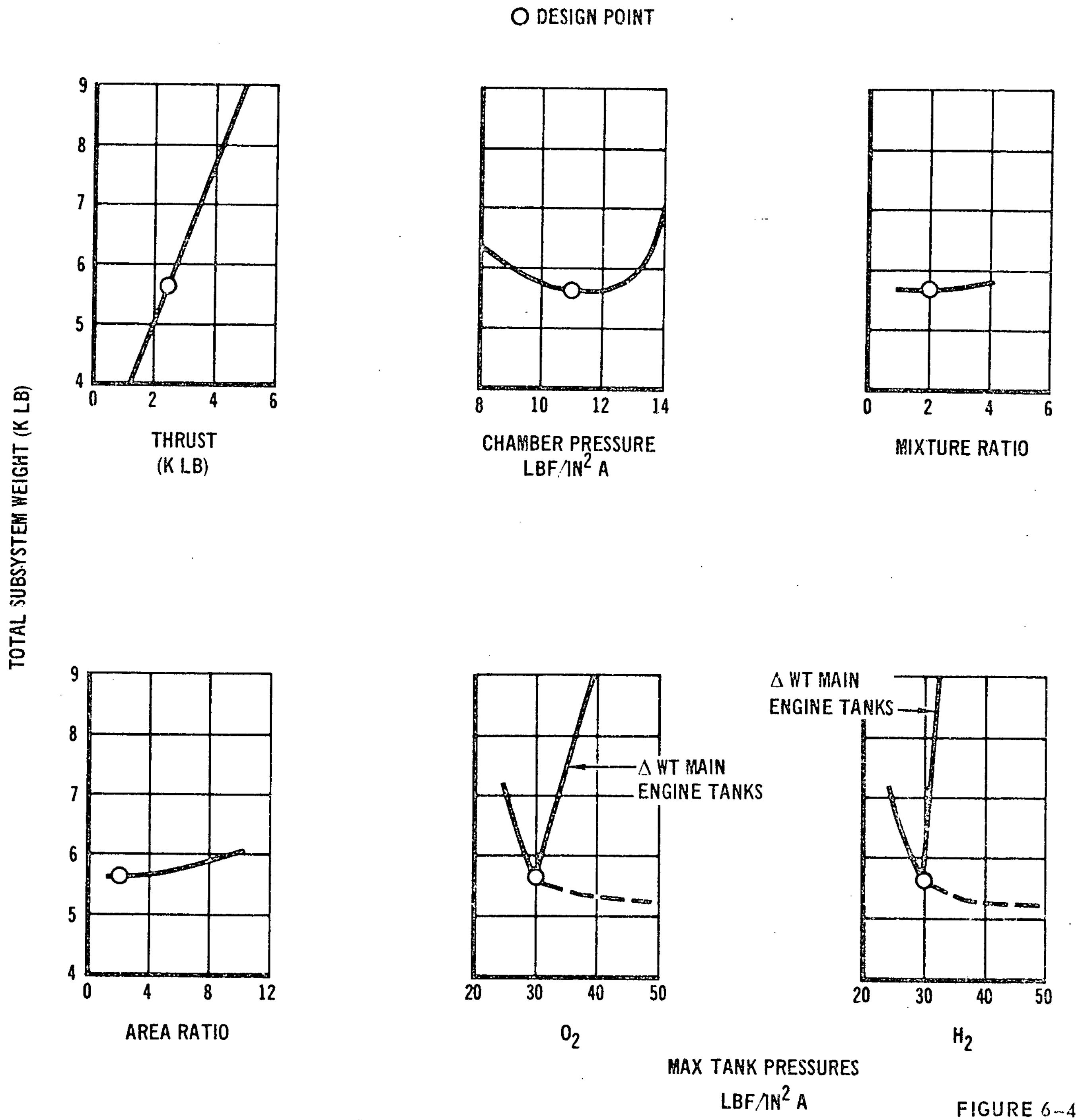


FIGURE 6-4

BOOSTER APS WEIGHT SENSITIVITIES

7. SUMMARY

This handbook defines for both booster and orbiter elements of the space shuttle vehicle preferred low pressure oxygen/hydrogen auxiliary propulsion subsystems capable of meeting space shuttle APS requirements and employing minimal new technology.

For the orbiter, the identified preferred approach requires that the APS provide all attitude control and vernier maneuvers, and an OMS perform all high total impulse maneuvers. The selected APS design uses liquid propellant storage, a passive heat exchanger integral with the main engine tanks, and a liquid/vapor mixer to control APS engine inlet conditions during major APS burns. During periods of low propellant demand, the subsystem operates in a gas blowdown mode. For the booster, the selected APS concept utilizes main engine tank residual propellants and operates in a simple gas blowdown mode. Both orbiter and booster subsystems use hydrogen film cooled engines. "Fail safe" reliability estimates exceed 0.9999 for the orbiter APS and 0.9999999 for the booster APS.

8. REFERENCES

(a) Space Shuttle Vehicle Description and Requirements Document (NASA), dated 1 October 1970